A METHODOLOGY TO SUPPORT RELEVANT COMPARISONS OF EARTH-MARS COMMUNICATION ARCHITECTURES

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A METHODOLOGY TO SUPPORT RELEVANT COMPARISONS OF EARTH-MARS COMMUNICATION ARCHITECTURES

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We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too.

– John F. Kennedy (Rice University, September 12, 1962)

A Bon-papa †

A mes frères, Vincent et Alexandre

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SUMMARY

Because of the human imperative for exploration, it is very likely that a manned mission to Mars occurs by the end of the century. Mars is one of the two closest planets to Earth. It is very similar to the Earth and could be suitable to host a manned settlement. Sending humans to Mars is a technological challenge above all. Among the technologies needed, some of the most important relate to communications. Women and men on Mars need to be able to receive support from the Earth, communicate with other human beings on Earth and to send back the data collected. A reliable and continuous communication link has to be provided between Earth and Mars to ensure a safe journey to Mars. However, the communication between the Earth and Mars is challenging because of the distance between the two planets and because of the obstruction by the Sun that occurs for about 21 days every 780 days. Because of the cost of communication systems and the number of exploration missions to Mars, it has been established that a permanent communication architecture between the Earth and Mars is the most profitable option. From these observations, the research goal established for this thesis is to enable reliable and continuous communications between the Earth and Mars through the design of a permanent communication architecture.

A literature review of the communication architectures between Earth and Mars revealed that a lot of concepts have been offered by different authors over the last thirty years. However, when investigating ways to compare the variety of existing architectures, it becomes very apparent that there were no robust, traceable and rigorous approach to do so. The comparisons made in the literature were incomplete. The requirements driving the design the architectures were not defined or quantified. The assumptions on which the comparisons are based were different from one architecture to another, and from one comparative study to another. As a result, all the comparisons offered were inconsistent. This thesis addresses those gaps by developing a methodology that enables relevant and consis-

tent comparisons of Earth-Mars communication architectures and supports gap analysis.

The methodology is composed of three steps. The first step consists in defining the requirements and organizing them to emphasize their interactions with the different parts of the communication system (the architecture, the hardware and the software). A study of the requirements for a deep-space communication architecture supporting manned missions is performed. A set of requirements is chosen for the present work. The requirements are mapped against the communication system. The second step consists in implementing and evaluating the architectures. To ensure the consistency, the repeatably and the transparency of the methodology developed, a unique approach enabling the assessment of all the architectures based on the same assumptions has to be provided. A framework is designed in a modeling and simulation environment for this purpose. The environment chosen for this thesis is the software Systems Tool Kit (STK) because of its capabilities. A survey of the existing architectures is performed, the metrics to evaluate the architectures are defined, and the architectures are evaluated. The third step of the methodology consists in ranking the alternatives for different weighting scenarios. Four weighting scenarios are selected to illustrate some interesting trades. The ranking of the architectures is performed through a decision-making algorithm, a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The results from the different weighting scenarios are discussed. They underline the incompleteness of the comparisons performed in past studies, the lack of design space exploration for Earth-Mars communication architectures and the importance of the definition of the set of requirements when designing and comparing architectures.

This research provides a transparent and repeatable methodology to rank and determine the best Earth-Mars communication architectures for a set of chosen requirements. It fills several gaps in the comparison of Earth-Mars communication architectures: the lack of definition of the requirements, the lack of a unique approach to implement and assess the architectures based on the same assumptions, and the lack of a process to compare all the architectures rigorously. Before the present research, there was no robust, consistent and rigorous means to rank and quantitatively compare the architectures. The methodology not only ranks but also quantitatively compares the architectures; it can quantifies the differences between architectures for an infinite number of scenarios. It has various capabilities including ranking Earth-Mars architectures based on a chosen set of requirements, performing gap analysis and sensitivities analysis on communication technologies and protocols, and performing design space exploration on architectures. The methodology developed is demonstrated on a restricted scope, it aims at being extended.

CHAPTER 1

MOTIVATION

1.1 Why go to Mars

"The future is vastly more exciting and interesting if we are a space-faring civilization and a multi-planetary species that if we are not. You want to be inspired by things. You want to wake up in the morning and think the future is going to be great. And that is what being a space-faring civilization is all about." [1]. Mankind has always been fascinated by the unknown. In their pursuit of knowledge, humans are called to cross borders. The first women and men left Africa to new continents about two billions years ago. Later, Spanish people crossed the ocean to discover the "New World". In the last century, Americans and Soviets initiated the space race. Every generation has its borders waiting to be crossed. As Elon Musk said in his speech at the 68th International Astronautical Congress, the new step for mankind is to become a multi-planetary species. Today, mankind faces a choice: to stay on Earth forever or to explore the Solar system. What history teaches us is that there will be people to leave the Earth. Exploration is not just for a few adventurers looking for new sensations, exploration is part of what define us. It is written in our DNA. The evidence is the 202,586 people from around the world who applied to be part of Mars One's mission. Mars One is a non-profit foundation. Its goal is to establish a permanent human settlement on Mars and the mission it offers is a single trip to Mars [2]. There are people ready to leave the Earth to explore the solar system. The true question is: "When do we leave?" Indeed, because of its inherent risks and costs, exploration has to be justified. There are four reasons justifying the human exploration of the solar system, starting with Mars: scientific, politic, societal, and economic.

The first question to answer is the one related to the destination itself. In other words, why Mars? Mars is a feasible destination. Its proximity to the Earth is the main key driver. The further we want to go, the more complicated the mission becomes due of the amount of propellant and time required to reach the destination. The requirements on the technologies needed to enable the mission are more stringent. Also, the human body has to cope with the hostile space environment (mainly radiation and micro-gravity) for a greater amount of time. As a result, an increased mission duration increases the mission's risks and costs. Figure 1.1 provides a scaled representation of the first six planets of the solar system along with the Sun. The distances between planets are so large that it is not possible to represent the complete solar system without being able to distinguish Mercury, Venus and the Earth. Due to these large distances, the two realistic options are to go to Venus or Mars. Venus is a terrestrial planet with a very dense atmosphere mainly composed of carbon dioxide. Because of its atmosphere, it is the hottest planet of the solar system, with surface temperatures reaching 864 degrees Fahrenheit. Adding a surface pressure ninety-two times that of the Earth and the presence of toxic sulfur dioxide in the air, Venus offers no chance of survival. Thus, the remaining option is to target Mars [3, 4].

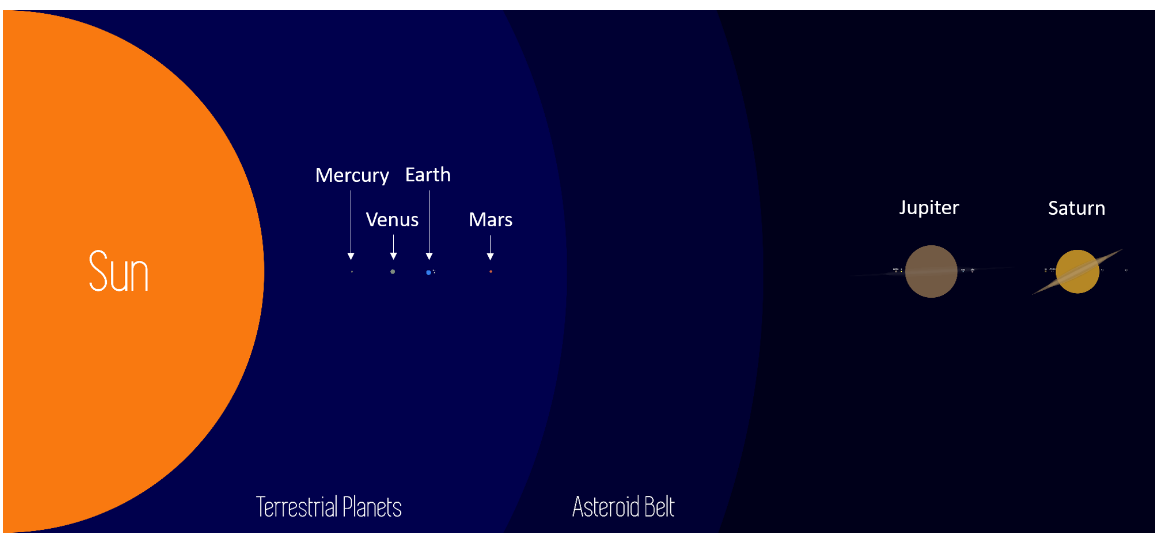


Figure 1.1: Partial representation of the solar system to scale

Contrary to Venus, Mars surface properties are quite similar to those of the Earth. Those similarities have been studied in order to better understand our own planet. During previous and current robotic missions to Mars, the weather has been monitored and the climate has been characterized. Recently, the Mars Science Laboratory Curiosity rover took detailed measurements of the cosmic rays and the energetic particle radiation environment over a 300-day period. These measurements enable the scientists to build models of the radiation environment on Mars surface and infer potential implications for the crew of a manned mission to Mars [5]. Past and current robotic missions have led to a better appreciation for the martian environment and have contributed to the planning of manned missions. On the Red planet, another asset is the presence of carbon, hydrogen, nitrogen, oxygen and water ice necessary to sustain human life. Their presence eliminates the need to carry these materials from Earth. By compressing the atmosphere, composed mainly of carbon dioxide with some nitrogen and argon, plants can be grown. From the water ice in the soil and the carbon dioxide in the atmosphere, methane and oxygen can be used to produce propellant [4, 6, 7]. As such, Mars is very suitable for low-cost manned exploration missions.

1.1.1 Scientific considerations

Due to its similarities with Earth, Mars is a top-choice destination for science. Mars exploration programs have focused on understanding the geologic and climatic events that shaped the planet [8]. Previous NASA program, "Follow the water", was designed to determine the presence of water on Mars. The Mars Global Surveyor mission confirmed the past presence of liquid water and some water-related activities, including glaciation [9]. Mars Odyssey found evidence of ice water at least in two locations on Mars: at either poles [10]. Liquid water is essential for life. The mutual involvement is also true: it has been demonstrated on Earth that almost anywhere there is water, microbes are present [11]. This is why the new NASA Program, "Seek Signs of Life", aims to find evidence of previous or current signs of life on the Red planet. In this quest for answers, the recent discoveries by the Curiosity rover are encouraging. Significantly more complex organic elements than those found before have been detected in high quantities, such as thiophene, benzene or toluene. If life exists, it necessarily implies complex chemistry in it. Hence, finding such molecules is a good sign. Besides, regular methane emissions have been confirmed. These emissions could have a mineralogical or a biologic origin [12, 13]. This is a second sign in favor of life on Mars but it is too early to conclude. Finding life on Mars would give the final answer to the question: "Are we alone in the universe?" and would provide invaluable information about the conditions under which life can be created and about the chemical processes leading to it. This is why the exploration of Mars is important.

At first, scientific missions could be performed only by robots. Robotic missions are less expensive and the consequence of a failure is less detrimental than for a manned mission. However, according to subject matter experts, a human presence is required alongside robots to obtain the answers we are looking for about life on Mars. Robert Zubrin, an aerospace engineer and the founder of the Mars Society said that "if we are serious about resolving the question of life on Mars [...] humans are required". At some point, scientists will be looking for fossils. This requires to travel long distances and carefully seek for clues. These abilities are beyond what a robot can do. Even on Earth, archaeological excavations are performed by people. A robotic program would take much longer to obtain the same results than a few manned missions. The confirmation of that statement is given by the example of the Moon. The present understanding of its geology is mainly attributed to the last three Apollo missions though many robotic missions had preceded. This is a testimony to the efficiency of manned missions to answer such questions [14]. Science represents the first reason as to why humans should go to Mars. However, it cannot be the only reason for a manned mission to the Red planet.

1.1.2 Political considerations

The second reason to go to Mars is political and humanistic. As explained by Sylvestre Maurice, an astronomer and planetologist at the Research Institute in Astrophysics and Planetology, "we do not send humans to Mars only for science, we send people to project our Humanity elsewhere" [15]. The projection of humanity elsewhere is highly political because each new world to conquer is synonymous with freedom, new rules, new influence and leadership to be established. As J. F. Kennedy said in his Moon speech at the Rice Stadium: "we set sail on this new sea because there is new knowledge to be gained, new rights to be won" [16]. Exploration is always a matter of power and domination to some extent. Today, new countries are emerging in space exploration. There is a great leadership, influence and attractiveness to be gained for the next decades, by the first country to safely send and bring back a person to Mars.

1.1.3 Societal considerations

Societal considerations derives from political considerations. Countries and companies that will carry out manned missions to Mars will have a significant advantage to attract the best people on the market. This can be seen by the infatuation for SpaceX today. Such endeavors inspire and motivate children and students to become engineers, researchers, mathematicians, etc. Indeed, the impact of the space program on the number of students following a graduate degree in mathematics, engineering and science have been proven by the Apollo program among others. Figure 1.2 illustrates the correlation between the NASA budget and the number of PhD students in space related disciplines during and after the Apollo program [3]. Human exploration programs are not only inspiring, they contribute to advance societies and improve lives. Every new space program has its technological challenges. From every technological challenge results new technologies. They contribute to strengthen the economy as they find applications in the industry. Space programs foster innovation. They have an overall positive impact on Society. Hence, since its inception, space exploration has provided great benefits to our everyday life at all levels: economic, environmental, for industry or for business, for medicine or agriculture etc. An example is the computer developed by the Apollo program. Many technologies in the medical field such as the MRI (Magnetic Resonance Imaging) improved by JPL (Jet Propulsion Labo-

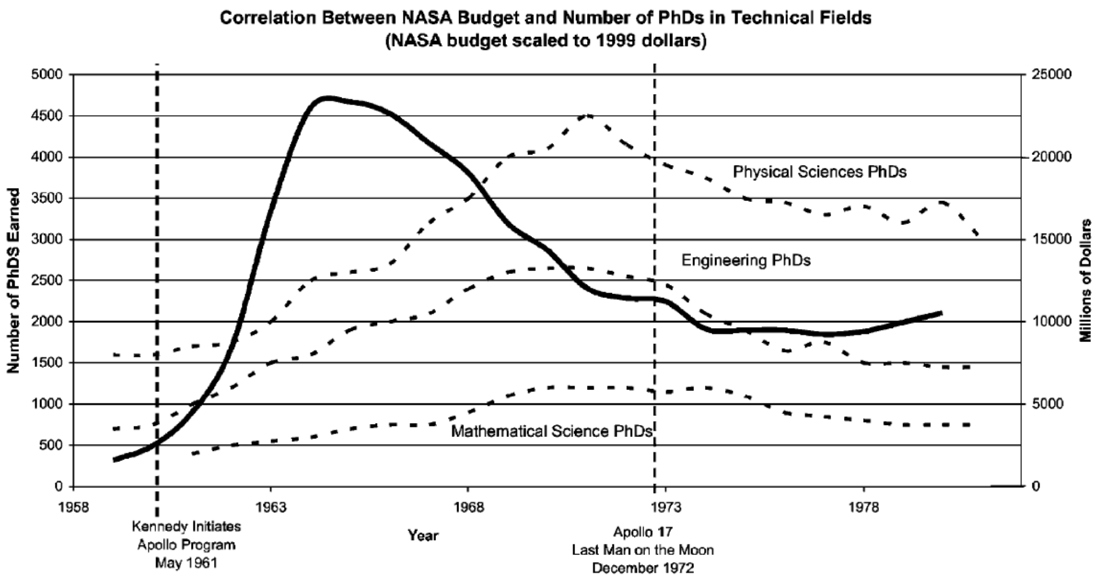


Figure 1.2: Correlation between the NASA budget and the number of students following a PhD program in physical science, engineering and mathematics [3]

ratory) in the 1960s, have been enabled by space programs. Other improvements include tumor detection using a software developed for the Hubble telescope or a ventricular assist pump, used in artificial hearts, derived from the American Space Shuttle's fuel pumps [17, 18].

1.1.4 Economic considerations

The last considerations are economic in nature. They are the most controversial ones. Indeed the initial investment to send people to Mars is important. The estimated cost for a such a mission ranges from $20 billion to $450 billion. The most optimistic estimation is based on "The Mars Direct Plan" designed by Zubrin whereas the most expensive budget is based on NASA's highest estimations [3, 14]. In the current economic context with cuts on all budgets, such an investment seems unreasonable. There are no short-term benefits. However, when thinking what this investment represents, one may realize that the amount by itself is not that important. A medium budget of $200 billion spread over thirty years represents $6.6 billion a year. The NASA budget is planned to be about $20 billion a year for the next five years, 20% of which is being allocated to deep-space missions [19].

Investment in space programs have been proven to be among the best investments a country can make. During the Apollo program, it has been estimated that one dollar invested generated about seven dollars in economic activities in new industries/products/jobs [20]. Today in France, the CNES (Centre national d'Etudes Spatiales, the French National Centre for Space Studies) estimates that every euro spent in the national space programs generates twenty euros in the French industry [18]. The impact is significant.

Lastly, there is no cost to be the first nation to send one of its citizens to another planet. The aura and leadership gained for this nation will last, not to mention the technological breakthroughs held by the country and its industries.

1.1.5 When ?

Facing risks and costs associated with a manned mission to Mars, each of these reasons alone (scientific, politic, societal and economic) is not sufficient. We cannot send people to Mars only to hunt fossils. The competition between countries to assess a leadership position is not strong enough. The benefits on our everyday life, innovation, industry and economy are too far in the long-term to counter the initial investment cost. Nevertheless, if all these reasons are put together, a manned mission is justified today. The remaining question is: "When do we leave?".

The first conceptual design of a manned mission to Mars was formulated by Wernher von Braun in his book *Das Marsprojekt* ("The Mars Project" in English) published in 1952. In 1989, George H.W. Bush was the first political leader to set Mars as a target for manned exploration. On the 20th anniversary of the Apollo 11 Moon landing, while he was President of the United States of America, he declared: "And next, for the new century [...] a journey to another planet: a journey to Mars". This plan is known as the Space Exploration Initiative (SEI). It was a bold and ambitious plan that was never implemented because it was rejected by Congress due to its cost [21]. Since this day, it has always been said that we will be on Mars in twenty years but thirty years later we are still far from being there. Two elements are needed for an objective to be met. The first one is a political will. The second one is the means to achieve the goal. Since President J. F. Kennedy and its decision to go to the Moon [22, 16], no president put enough money on the table to reach the target. At the time of Kennedy, an important key driver for such decision was the political situation. During the Cold War, the United States of America had to defend their leadership position and assert their power against the Soviets. Today, there is no more competition between countries, the general atmosphere is more about international collaboration. However, the pressure on human exploration is growing. Some countries are emerging in the space conquest, such as China or India, that have initiated robotic programs to Mars. India successfully launched the Mangalyaan mission in 2014 with a satellite orbiting around Mars. The following mission, Mangalyaan II is very likely to be a martian lander. A few private companies are starting to take part in the market of manned missions that was previously reserved to governmental agencies. Among them are Bigelow Aerospace, Boeing, Lockheed Martin, Orbital ATK but mainly SpaceX, led by Elon Musk. At the last International Astronautical Congress, he presented his plans to send the first cargo to Mars by 2022 and the first people by 2024 [1]. He also provided a technological roadmap along with ways to fund the project. His plan includes four technological key drivers: full reusability, refuelling in orbit, production of propellant on Mars, identification of the right propellant. For now, it is impossible to know whether his plan will succeed or not but with all the newcomers in the field of manned missions to Mars such a mission is very likely to take place in the next decades.

OBSERVATION 1: A manned mission to Mars is very likely to happen before the end of the 21st century.

In particular, a manned settlement has been projected to be established on Mars around 2050. This date is an approximation but has been established by various people in the past

[23, 24]. This date is far enough in time to be plausible and not too far so that the technologies that will be available at that time will still not be too different from the ones that are used today, meaning the radio frequencies used today will still be used at that time.

ASSERTION 1: For this study, it is assumed that a manned settlement is established on Mars.

Most issues related to sending people to Mars are still far from being solved. There are still technological, scientific and economic challenges to be overcome. The economic challenges have already been discussed. The scientific challenges are very important as they concern the health of the crew. Research still has to be carried out to understand the effect and impact of such hostile environment on the human body. Radiation protection, reduced gravity countermeasures, medical care and life support in habitats and space vehicles are among the main focuses of the science-related challenges for a manned mission to Mars. Indeed, the most difficult part of the mission is not to send people to Mars but to bring a healthy crew back to Earth or make sure the manned settlement remains healthy while on the surface of Mars. Finally, the main challenge is technological. It is the focus of the present work.

1.2 Why communications are needed

1.2.1 Communication systems, an enabler for crewed missions to Mars

Telecommunications are one of the main technological challenges of space exploration. As underlined by President Obama in 2010: "Sputnik, the first artificial satellite to orbit the Earth, [...] was little more than a few pieces of metal with a transmitter and a battery strapped to the top of a missile" [25]. With energy and propulsion, communication is one of the first elements to be needed on a spacecraft. Telecommunication systems are required for all missions, manned and unmanned. Indeed, without any information from the spacecraft sent into space, it is impossible to know where it is and what are the outcomes of the mission. Consequently, a mission without a functioning communication payload is considered as lost. When an unexpected event occurs during a mission, telecommunication systems enable experts on Earth to assess the spacecraft and intervene if it is needed and possible. For example, the trajectory can be corrected from a distance. In short, telecommunication systems are needed to make the most of the mission by enabling interactions with the spacecraft, transmission of the mission outcomes and adaptability in unexpected situations.

In the case of a manned mission, the communication systems are even more important as the lives of the crew are at stake. Besides, the psychological effects of a journey to Mars could be important on astronauts travelling in space. Indeed, it is not easy to live in a confined environment with the same people for a long period of time. The microgravity and the risks resulting from the mission are stressful and can lead to psychological pathologies such as anxiety, insomnia or depression. To fight these effects, the astronauts on the International Space Station (ISS) can communicate via phone calls and emails with their relatives. They are also able to see the Earth at all times. On a journey to Mars, this will not be possible. Today, with available communication technologies, the communication time between the Earth and Mars ranges from 7 to 40 minutes back and forward. A journey to Mars lasts about three years, which is six times longer than the average stay on the ISS [26]. In that context, improved communication systems could help make the journey to Mars more pleasant for astronauts. As a result, communication systems are critical to a crewed journey to Mars. This leads to Observation 2.

OBSERVATION 2: A reliable and continuous communication link has to be ensured between the Earth and the spacecraft to enable a safe crewed journey to Mars.

Two questions emerge from this observation: "What are the requirements on the telecommunication systems?" and "Why is it a technological challenge to achieve them?" At the top level, the communication system has to provide the following services: time insensitive transfer of large size data, time sensitive video streaming for the control of rovers, time sensitive communication for the crew, telemetry, tracking, command. These services are required by the users expressing their needs in terms of high level requirements. At a lower level, for the designer of the communication system, these requirements can be translated and classified into two categories: the transmission performance and the integration. The requirements on the transmission performance encompasses requirements on the communication data rate, the daily data volume, the propagation delay, the link availability etc. The requirements on the integration in a space system (satellite, spacecraft, ground station) include those that impacts all the systems. They include the size and volume, the mass, the power consumption, the lifetime, the level of maintenance required, the robustness etc, and ultimately the cost. The level of these requirements is expected to be higher than everything forecast until now. This is why communications systems are a technological challenge that needs to be overcome. Besides, today, every mission carries its proper communication payload. In other words, the communication effort is not pooled.

1.2.2 Challenges

As mentioned, communications represent a technological challenge. The gap between the requirements and the performance of current communication systems is important. Filling this gap is hard for two reasons. As seen in the previous section, the levels of the requirements are high. Second, the configuration of the Earth and Mars in the solar system induces some limitations on what is feasible in terms of communication. The distance between the two planets varies from 0.38 AU (Astronomical Unit) to 2.67 AU (ie. between 57 and 400 million kilometers). With current communication technologies, the resulting communication time varies from 7 minutes to 40 minutes back and forward. Also because the received power on a communication link decreases proportionally with the square of distance between the transmitter and the receiver, an increased distance between the two planets requires a much higher power to produce a signal of the same magnitude [6].

Another challenge is to maintain a continuous communication link. Due to the configuration of Earth and Mars in the Solar system, the data signal is corrupted by an interaction between solar charged particles and the signal. This problem occurs periodically during what is called "Solar conjunction". The Solar conjunction is when the Sun lies on the line passing through Earth and Mars. There are two possible configurations (Figure 1.3):

1. Superior solar conjunction: when the Sun is between Earth and Mars
2. Inferior solar conjunction: when Earth is between the Sun and Mars

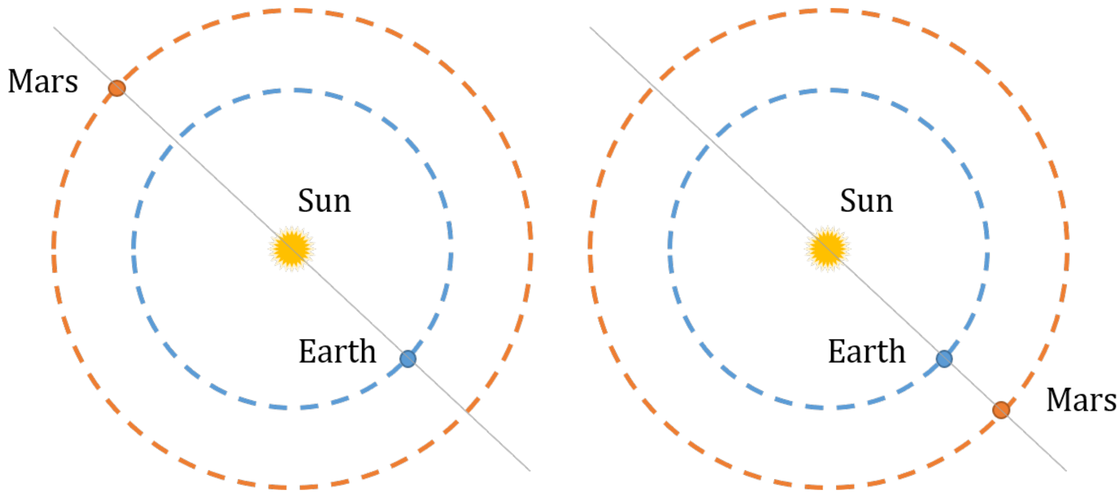


Figure 1.3: Superior solar conjunction on the left, Inferior solar conjunction on the right

The most challenging scenario is the superior solar conjunction. During this period, the distance between the Earth and Mars is at or near its maximum. As a result, the transmission is at its weakest level. In addition, solar charged particles corrupt the link. There are three main effects of solar charged particles on communication links. These three effects increase when the angle $\widehat{SEM}$ (Sun-Earth-Mars) represented on Figure 1.4 decreases.

- The first effect is called intensity scintillation, or fades. It results in a degradation of the transmitted signal. When $\widehat{SEM}$ becomes too small, the magnitude of the signal reaches a saturation point.
- The second effect is called spectral broadening. It refers to an increase in the signal bandwidth.

- The third effect is the phase scintillation. It refers to a modification in the phase of the transmitted signal. This effect does not saturate contrary to the intensity scintillation.

These three effects degrade the signal transmitted. They depend on the Sun-Earth-Mars angle, the signal frequency band used to transmit the signal, and the solar activity. The average value of the minimum $\widehat{SEM}$ angle to ensure a direct communication according to the frequency of the signal is called α and is given Table 1.1 [27].

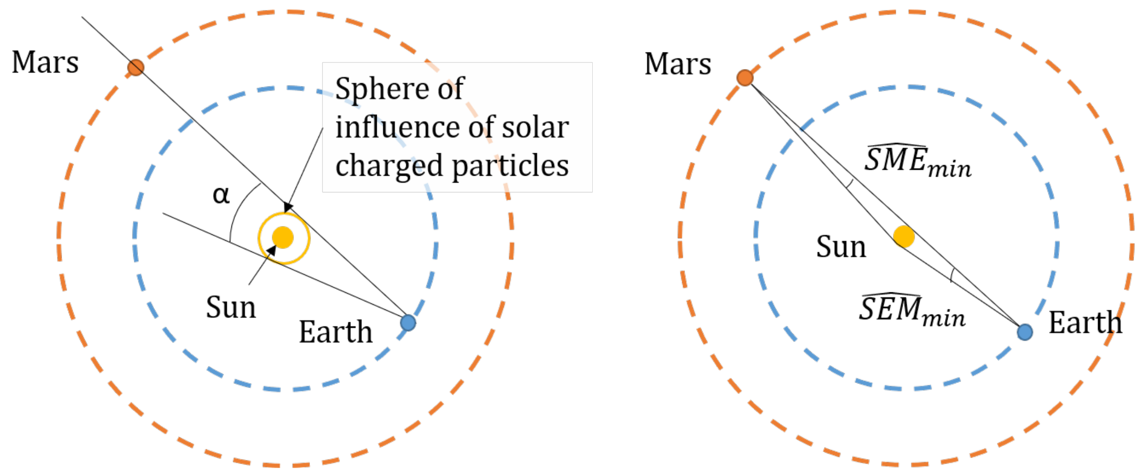


Figure 1.4: Definition of the angles during a solar conjunction

Superior solar conjunction is a periodic event. It occurs every synodic period. The synodic period S is defined as the shortest time between which the relative position of two objects repeats. It is given by Equation 1.1 with T_E, the Earth period and T_M, the Mars period [28]. The Earth revolves about the Sun in one year. Mars revolves about the Sun in 1.8808 Earth's year. The inertial geometry repeats approximately every fifteen years.

$$S = \frac{T_M T_E}{T_M - T_E} \approx \frac{15}{7} \tag{1.1}$$

Table 1.1: Relationship between the minimum angle and the frequency

Frequency (GHz)	α **(degree)**
2.3 (S-band)	5
8.4 (X-band)	2
32 (Ka-band)	1

During a superior solar conjunction, when Mars transmits information to the Earth, the Sun appears as a disk of $\widehat{SEM}_{min} = 0.264$ degree in radius from the Earth. When the Earth transmits information to Mars, the Sun appears as a disk of $\widehat{SME}_{min} = 0.175$ degree in radius from Mars. When $\widehat{SEM}_{min} < \widehat{SEM} < \alpha$ some techniques can be implemented to maintain a minimum communication [29]. When $\widehat{SEM} < \widehat{SEM}_{min}$ or $\widehat{SME} < \widehat{SME}_{min}$, there is a solar occultation. A direct communication is not possible. An alternative has to be found in order to enable a continuous communication. A relay satellite in heliocentric orbit is a possibility.

Occultation can result from an alignment of the two planets with the Sun but also with another space object such as a moon or an inner planet. Usually, the communication beam is large enough to maintain the communication link but the intensity of the signal transmitted is significantly reduced.

1.2.3 Impacts and benefits

Robotic and manned missions

The benefit of improving current communication systems is that their development is useful for both robotic and manned missions. An improvement can be implemented as soon as it is mature, can be tested on a robotic missions. Then it can be used for the following missions. The return on investment is immediate. The new technology is useful even if a crewed mission never takes place.

Reduced mission costs

As already mentioned, each spacecraft today has its own communication payload. This payload has a mass and a power consumption that respectively reduce the mass available and the power available for the scientific payload. Along with some technological developments in communication systems, an interesting exercise would be to design and implement a communication architecture to ensure the communication link between the Earth and Mars. With such an architecture, both the mass and the power consumption needed for communications on each mission decrease. Thus, the cost of the mission can decrease. Another point of view is that the part of the mass and the part of the power consumption allocated to the communication payload is now allocated to the scientific payload. Thus the profitability of the mission is increased. In all cases, there is an economic advantage to the implementation of a communication architecture between the Earth and Mars. The cost reduction will open the market to new players such as new countries or private companies.

Such an architecture could work on the same basis as the NASA Deep-Space Network (DSN). The DSN is an international network of ground stations to command, track and monitor NASA spacecraft in deep-space and a few missions in Earth orbit. The use of the DSN is not limited to telemetry, spacecraft command and tracking, but also supports science, including radio science, radio astronomy and radar mapping of passing asteroid. The network is composed of three facilities placed approximately 120 degrees apart in longitude around the globe to provide a permanent communication link with the spacecraft as the Earth rotates (Figure 1.5). The three facilities are in Goldstone in California, near Madrid in Spain and near Canberra in Australia. Each station is composed of several antennas that emit and receive signals on three frequency bands: S-band (about 2.2 GHz), X-band (about 8.4 GHz) and Ka-band (only for deep-space mission, about 32-34 GHz) [30].

The European Space Agency has its own network of ground-based space-tracking stations known as the European Space Tracking network (ESTRACK). The network is composed of nine ground stations distributed all over the globe augmented by three cooperative stations owned by ESA's partners. The mission of this network is to provide a global space link connectivity for European deep space missions, Near-Earth missions and Low-Earth missions [31]. Contrary to NASA's Deep Space Network, the use of this network is not restricted to deep-space missions. Besides, an agreement exists between the United States of America and the European Space Agency for mutual support and cooperation, especially in the case of inoperability of a ground station resulting from a natural disaster, a climatic

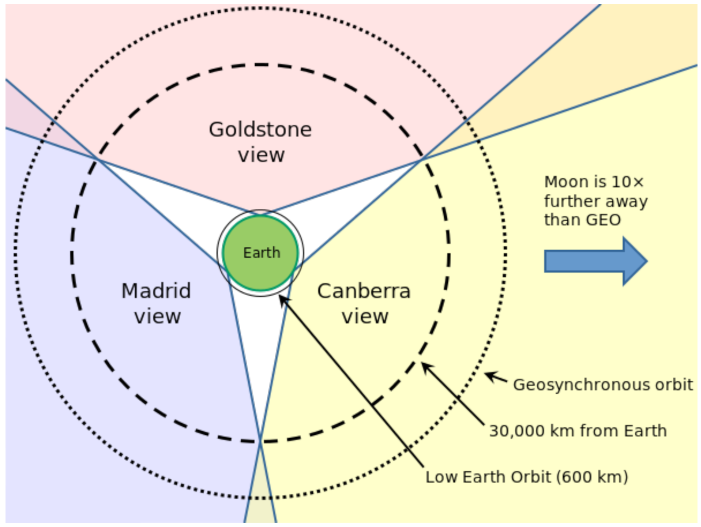


Figure 1.5: Locations of DSN ground stations and the complete deep-space coverage [30]

event etc. [32]. A few other countries such as China, Russia, Japan and India have their own network as well. The countries that do not have their own network can use NASA DSN or the network from other countries, after agreements have been signed

In the case of a communication architecture between the Earth and Mars, because of the costs and the complexity of such architecture, one could envision a collaboration between two entities. Building on a strong history of collaboration, the cooperation between the DSN and the ESTRACK, collaboration on missions such as the Mars Science Laboratory or Cassini-Huygens, a partnership between ESA and NASA could be a solution. This would lead to a better communication system because it would have its own performing facilities and a communication system at lower cost that would contribute to reduce the cost of robotic and manned missions to Mars.

Deep-space applications

Developing a communication architecture could also enhance communication for deep-space missions. Today, the communication with deep-space probes on Earth is provided by ground networks such as the NASA DSN. These communications suffer the same limitations as the communications between Earth and Mars: a large distance and solar conjunction events. A communication network between Earth and Mars could be a new node in that network. It would also remove the occultation resulting from most of the solar conjunction events, the times when Mars is outside the yellow cone represented on Figure 1.6.

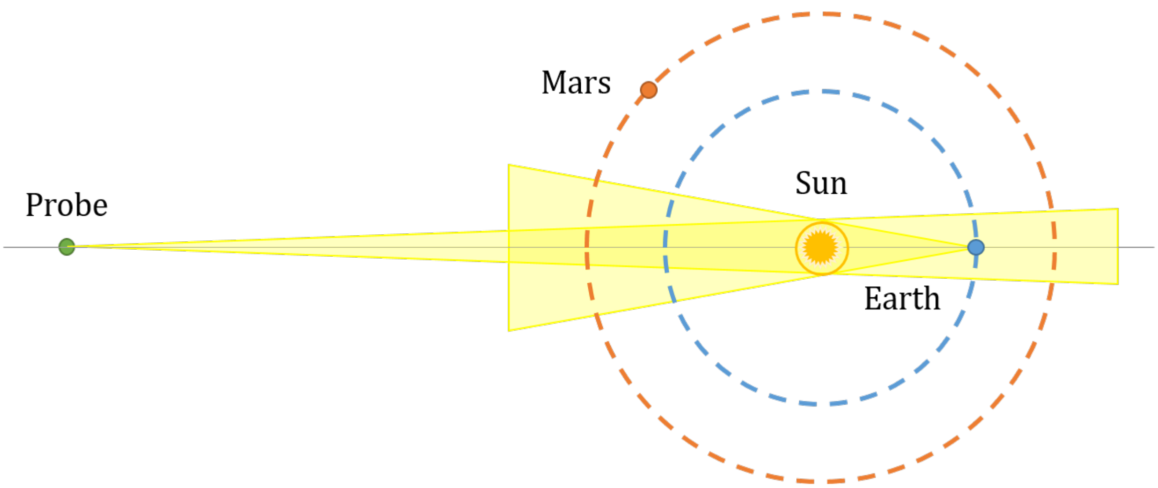


Figure 1.6: Earth-Probe solar conjunction

From previous considerations we noticed that today, each mission has its own communication system and that there would be great benefits in having one communication architecture between the Earth and Mars: reduction in the cost of robotic and manned missions to Mars and improvements in the communication links. Such cost reduction is expected to attract newcomers in the field of space missions to Mars. Such architecture is expected to improve the NASA Deep-Space Network overall. This leads to Assertion 2.

ASSERTION 2: A permanent communication architecture between the Earth and Mars is the most profitable option to enable the communication between the two planets.

1.3 Summary

It is expected that a crewed mission to Mars takes place within the next decades, driven by the pressure from newcomers and the existence of cost plans to support such exploration missions. The countries taking part in these missions will reinforce their leadership and attractiveness, strengthen their economy, inspire the World. Humans will go to Mars to look for answers about the origin of life, to understand our world and to fulfill the human imperative of exploration.

In order to enable such missions, communication systems have to be improved. The improvements needed are challenging because of the requirements set on the communication systems. These requirements are difficult to meet because they are stringent; the distance between the Earth and Mars is important and solar conjunction events prevent any direct communication between the two planets every 2.14 years. It is hypothesized that the best strategy to overcome these challenges is to build a communication architecture between the two planets as well as to enhance communication technologies. It is expected that such an architecture would lead to reduced costs for robotic and manned missions to Mars and enhanced deep-space communications. As a result, the research goal of this thesis is the following:

RESEARCH GOAL: Enable reliable and continuous communications between the Earth and Mars through the design of a permanent communication architecture.

This thesis is organized as follows. Chapter 2 reviews the relevant literature, identifying the methodological gaps in architectures comparisons. Chapter 3 defines the problem, reducing the scope of the study and deriving research questions and associated hypotheses. Chapter 4 describes the methodology developed. Chapters 5, 6 and 7 detail the implementation of the steps 1, 2 and 3 of the methodology, respectively. Lastly, Chapter 8 concludes on the contributions and provides avenues for future work.

CHAPTER 2

BACKGROUND AND GAPS IDENTIFICATION

To meet the research goal, there is a need to start by reviewing the communication options between the Earth and Mars. Focusing only on the communication capability, at the simplest level, a communication system is composed of three elements: the architecture, the hardware and the software. In this thesis, the communication system refers to the combination of the architecture, the hardware and the software, as illustrated on Figure 2.1. The hardware designates what is also called the communication technology or the technology in the remaining of the document. The software designates what is also called protocol in the remaining of the document.

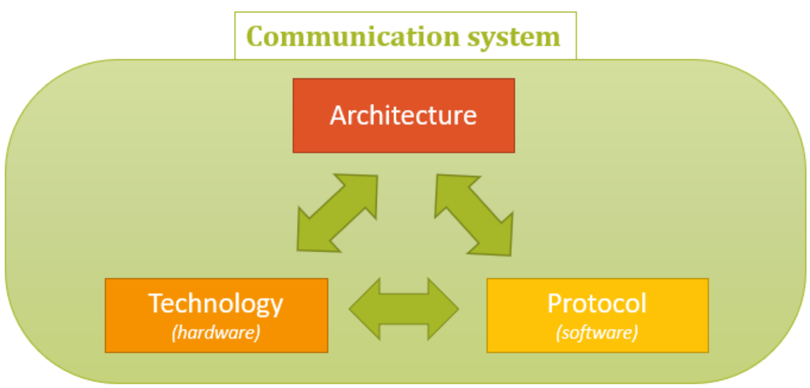


Figure 2.1: Decomposition of a communication system in this thesis

This chapter reviews the different aspects of existing and future communication systems used in deep-space missions. It details the different communication technologies available, the concept of Interplanetary Internet that is close to what we want to do around the Earth and Mars and reviews the concepts of architectures proposed by different authors for Earth-Mars communication. The chapter ends by the identification of methodological gaps in the comparisons of Earth-Mars communication architectures. The overarching research objective of the thesis results from these gaps.

2.1 Communication technologies

This section focuses on the two main communication technologies used during deep-space missions: radiofrequency and optical communications.

2.1.1 Radiofrequency

Radiofrequency (RF) is the long-lasting telecommunication technology used for space missions. From the beginning of the deep-space program, the frequencies used have been constantly increased. The first frequencies used were L-band (900 MHz) and S-band (2.3 GHz). In 1977, the X-band (8.4 GHz) was introduced on Voyager. The Ka-band (32 GHz) has been demonstrated by Mars Reconnaissance Orbiter (MRO) for deep-space communication in 2006. S-band, X-band and Ka-band are the three technologies still used for deep-space mission today. The higher the frequency, the better the performance. Indeed, a higher frequency induces a larger bandwidth, a higher data rate, a lower mass and a lower power consumption. When MRO demonstrated the Ka-band technology, it transmitted the most amount of data returned in a single day (116 Gbits) and highest data rate (5.2 Mbps) ever, between the Earth and Mars [33]. For future deep-space missions, only X-band and Ka-band will be considered as S-band is becoming obsolete. A detailed comparison of the two technologies have been established by Hemmati et al. [34].

2.1.2 Optical communications

Optical communications can be referred to as free-space optical communications, laser communications or lasercom. It refers to communications using the optical frequencies to transmit the signal, as opposed with radio frequencies. Optical frequencies range from ultraviolet to short infrared (Figure 2.2). In terms of hardware, a parallel can be drawn between the elements of a RF system and the elements of an optical system. For example, a telescope replaces an antenna, etc. The major difference between the two technologies is the size of the beam. As the diffraction is proportional to the wavelength, laser beams can be up to 10,000 times narrower than radio beams. As illustrated on Figure 2.3, the pointing has to be much more precise with the optical technology [35].

This technology is quite new. It has been demonstrated in deep-space for the first time in 2013 with the NASA Lunar Laser Communication Demonstration (LLCD). The mission was to be able to communicate between the Earth and a satellite in lunar orbit using duplex laser communication. The demonstration was successful. The data rate achieved was the highest ever achieved from the Moon: 622 Mbps [36].

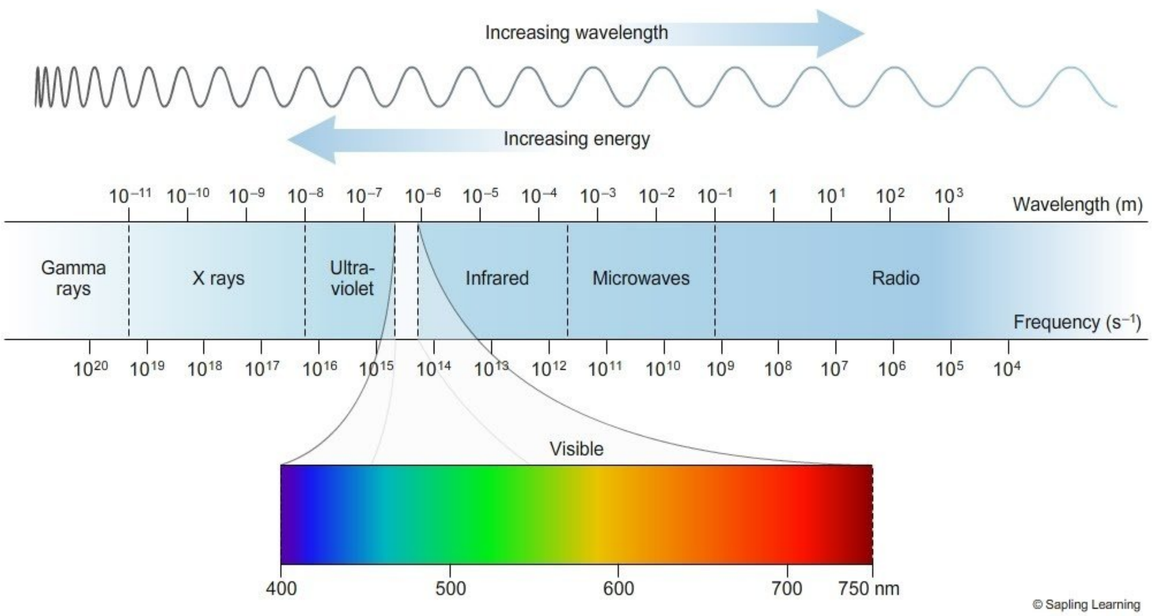


Figure 2.2: Wavelength Spectrum

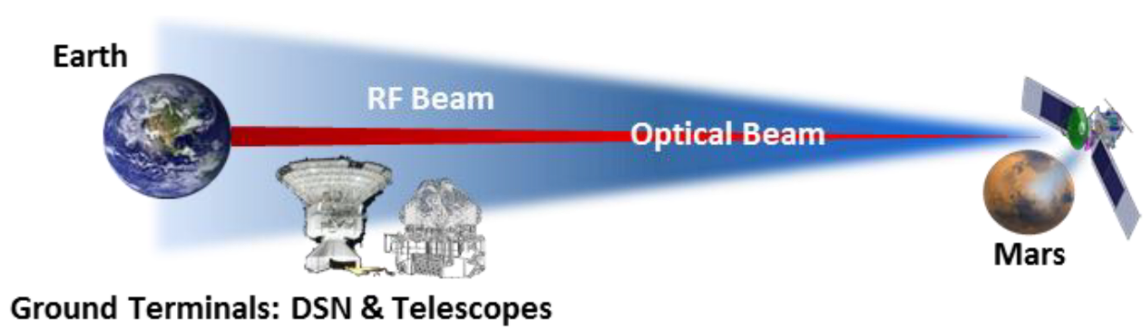


Figure 2.3: Comparison between RF and optical beams [35]

2.1.3 Comparison

At first, optical communications seem to be the best option. Indeed, it reduces the mass, the size and the power consumption of the communication module for the same requirements on the communication links. Overall, the communication performance achieved by laser links are substantially higher than those of RF. The data volume and the data rate are higher. The latter is not bounded by regulations contrary to radiofrequency, and laser communications have an almost infinite bandwidth [37]. A quantitative comparison is provided in Figure 2.4 [34]. Also, it has been estimated by NASA that RF technology could no longer be performant enough in term of science data return by ten to twenty years, that is to say, quite soon. However, performance is not the only criterion that matters. The imple-

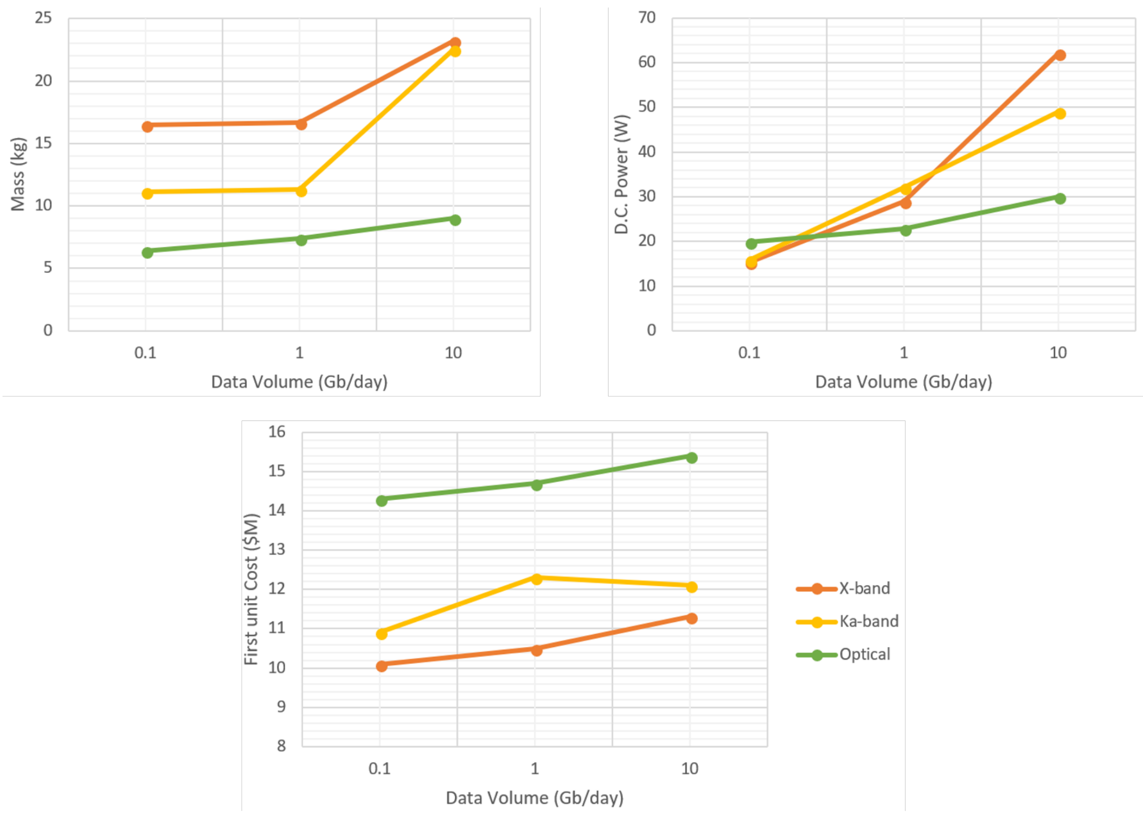


Figure 2.4: Comparison of the performance of X-band, Ka-band and Optical communications for a Mars mission in terms of mass, power and cost according to the data volume in the worst case scenario of a Mars-Earth distance of 2.7 AU

mentation of the optical technology is not straightforward. In the last decades, significant resources have been deployed and invested to establish robust RF infrastructures around the world. Because of those investments, RF facilities have to be used and will not be replaced soon [37]. Besides, there is a difference in maturity between the two technologies. RF have been proven to be reliable on most of the deep-space missions. On the contrary, optical link is still in a demonstration phase, its Technology Readiness Level (TRL) is low as it has never been tested further than the lunar orbit. There is also no historical data on the lifetime of the technology. Furthermore, the optical technology's beam is narrower (Figure 2.3) and induces a stringent pointing requirement of few microradians. Consequently, the hardware for optical technologies is more complicated. Stabilizers are required and the system is more sensitive to weather events [38]. Table 2.1 summarizes all those aspects.

Table 2.1: Comparison between Optical communications and RF for relevant figures of merit (FOM), the green check indicating the best option for each FOM

	Radiofrequency	**Optical link**
Performance (data rate, data volume...)		✓
Mass, Power, Size		✓
Cost		✓
Readiness	✓	
System complexity and implementation	✓	
Robustness, Sensitivity to weather	✓	
Regulation		✓

The exploration and development of new technologies tend to call for a hybrid architecture combining RF and optical communication systems. The key is to design such a combination so that the hybrid system is beneficial to the mission without increasing the mass, the power consumption and the cost of the communication module. The advantage of a hybrid system is to rely on two technologies instead of one [37].

2.1.4 Faster-than-Light communications

One of the requirements on Earth-Mars communications is to reduce the propagation delay. Both radio-frequency and optical technologies use electromagnetic waves to propagate the information. The relationship between the wavelength λ and the frequency f is given by:

$$\lambda = \frac{c}{f} \tag{2.1}$$

where c is the speed of light in free space, i.e. the speed at which an electromagnetic wave propagates in space. In the relativist theory, this velocity is fixed to approximately 300,000 km/s. As the distance between the Earth and Mars ranges between 0.38 AU (57 million of kilometers) to 2.67 AU (400 million of kilometers), the minimum communication time ranges from 4 minutes to 21 minutes, no matter the technology used.

To overcome this limitation a new concept called Faster-than-light (FTL) communications is being developed. Such a system could enable virtual reality presence on Mars. The benefits of such a technology are two-fold. 1) enabling tele-operated robots on Mars during robotic missions, and 2) enabling real-time communication between the experts on Earth and the crew on Mars during manned missions. Phone calls and emails between the two planets would be possible. Contrary to electromagnetic waves that are based on the relativity theory, FTL communications are based on quantum mechanics principles. They take advantage of quantum non-locality and indistinguishable particle statistics to propagate the information [39]. In order to be feasible, the FTL mechanism has to be relativistically consistent and to preserve causality. These two properties are translated into constraints on the architecture of the system: FTL communications require a transmitter located near the midpoint between the two planets at all time. The constraint on the architecture design is significant. Choosing this technology would drive the entire communication architecture.

However, the benefit of immediate communication gained in return cannot be equalled by another technology.

Because this technology hasn't been tested and demonstrated to work, none of its properties (power required, mass etc.) are known. Thus, it will not be considered in this study. This study will only focus on existing technologies that have been proven to be functional that is to say, a TRL of at least 5 to 6 [40]. No communication technology development is considered in this study. Another consequence is that the value of requirement on the propagation delay cannot be inferior to 22 minutes at worst, as it is a limitation induced by the communication technologies.

2.2 Interplanetary Internet

The previous section detailed the communication technologies. As stated in Assertion 2, a communication network is the best option to ensure a continuous and reliable communication link between the Earth and Mars. This section reviews the infrastructure needed to support and include the communication technologies in a communication network. This infrastructure is commonly referred to as the "Interplanetary Internet". It encompasses the communication network protocols and the architectures.

The concept of the Interplanetary Internet depicts a communication network of planetary networks. It would be the Internet across the Solar System. The idea is to interconnect landers, orbiters, rovers, ground stations, relay satellites etc. It includes all kinds of communication links: Up-Links (ULs), Down-Links (DLs), Inter-satellite/spacecraft Links (ISLs) and Interplanetary Links (ILs). The end-goal is to come up with an optimized hybrid architecture system composed by satellites, spacecraft and ground stations around and on several planets (including the Earth), as well as relay satellites in halo orbit and heliocentric orbit. One of the multiple concepts is presented on Figure 2.5.

Such a system has to provide a certain number of services as described in the "Motivation" Chapter: time-insensitive transfer of large data, time-sensitive live video streaming,

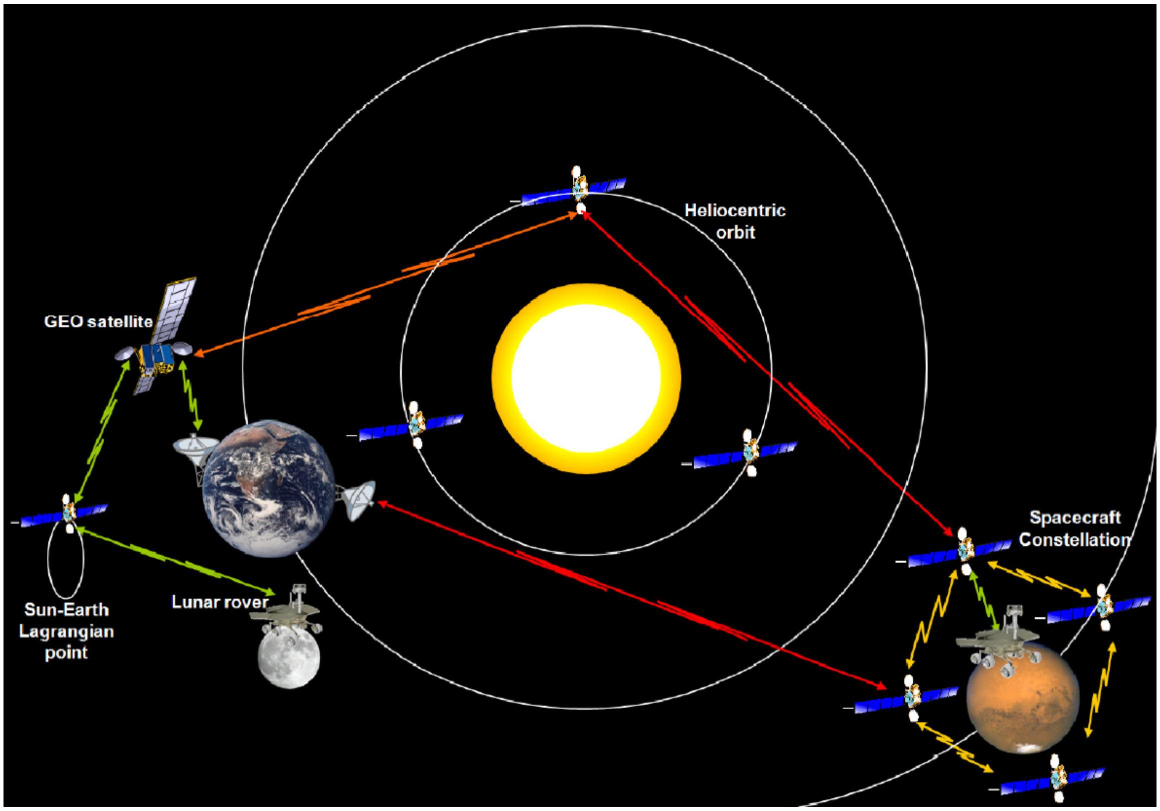


Figure 2.5: A possible alternative of the Interplanetary Internet network [41]

telemetry, command and tracking. These functions are broken down into several highly stringent requirements. The main ones are [41]:

1. The large propagation delay,
2. The discontinuity of the link,
3. The large path losses,
4. The limited quantity of energy available.

The large propagation delay is a consequence of the distance between the planets. As seen in the previous section, the communication delay between the Earth and Mars in the worst case scenario cannot be shorter than 22 minutes with the current technologies. The communication has to be as direct as possible. Discontinuities in links are the results of obscurations by other planets or solar conjunction events. Consequently, a relay satellite has to be available at all times to ensure a continuous communication link. The large path loss is a consequence of the two previous issues. It results from the distance between the planets and some elements that can affect the quality of the transmission, such as the presence of charged solar particles. Whereas the three first issues are related to the transmission performance requirements, the last one is related to the integration of the communication technology: the limited quantity of energy available. While being a parameter linked to the integration of the system, the energy available is a key parameter in the design of a communication system as the signal transmission intensity is directly induced by the power available. An additional factor to be considered is the cost. It has to be as small as possible as it is the main driver in most space programs.

To address the aforementioned issues and challenges, two approaches exist:

1. Develop a communication network protocol that manages delay, altered signals and discontinuities

2. Design a space systems architecture that minimizes the distances between elements of the communication architecture and avoids link blackout as much as possible

As illustrated on Figure 2.1 at the beginning of the chapter, the technology, the protocol and the architecture interact with each other as different parts of the same system. In this thesis, the focus is on the architecture. This is why there are two approaches: looking at the interactions with the protocol or looking at the interactions with the technology. Many studies have already been carried out on these two approaches. However, there is a lot of room for improvement on the two approaches. Due to programmatic constraints, only one approach can be tackled here. The second approach is selected because of the background of the author.

An architecture design encompasses the selection of the number and types of space elements (satellites, spacecraft and ground stations) along with the definition of their characteristics, including their locations and trajectories. In the context of this study, the possible locations for the space elements are on Earth and on Earth orbit, on Mars and on Mars orbit, on heliocentric orbit and on halo orbits on Sun-Earth Lagrangian points or on Sun-Mars Lagrangian points. The Moon, Phobos, and Demos could also be considered. The benefit of the Martian moons is that they are tidally locked and always show the same face to Mars. As a result, a ground station can be built on either of them constantly facing Mars [6]. This could be the only use that would change the design of the architecture. However, for the sake of simplicity, they will not be considered in the context of this study.

2.3 Communication architectures

The first section of this chapter reviewed the communication technologies available for deep-space communications. The second section introduced the concept of Interplanetary Internet corresponding to a permanent architecture between the Earth and Mars. It highlighted the challenges related to the concept and offered two ways to overcome those challenges: working on the protocols or working on the architectures. As the choice is made to tackle the architectures, this section offers a quick review of the different types of architectures proposed by various authors. The intent is to introduce the wide range of existing solutions as illustrated on Figure 2.6, drawing the attention on the advantages and the drawbacks of each type of concepts. An extensive survey will be performed in Chapter 6, with some elements of it in Appendix C.

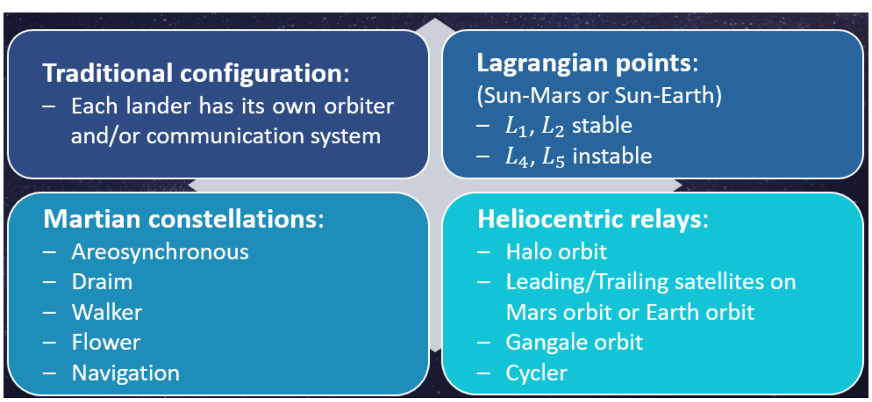


Figure 2.6: Different types of concepts for Earth-Mars communication architectures

2.3.1 Traditional architecture

The first concept is the one used in all past missions to Mars. The traditional solution is to have a dedicated communication payload on each mission. The scheme is a combination lander-orbiter. The lander communicates with the orbiter and the orbiter ensures the link between the Earth and Mars (Figure 2.7).

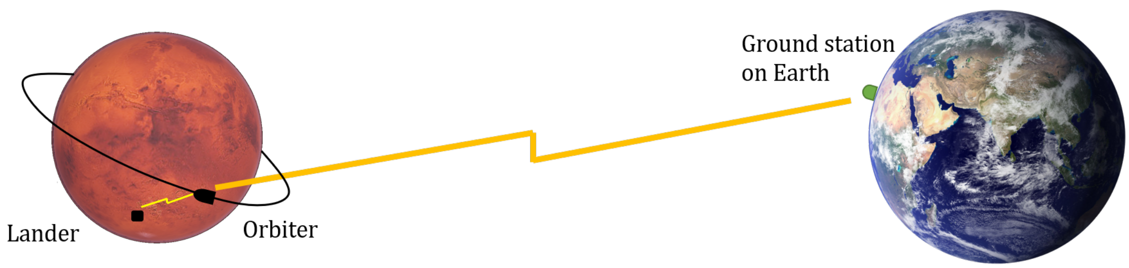


Figure 2.7: Traditional lander-orbiter configuration

The benefit of this configuration is its mission-specific characteristic: the communication payload is adapted to the requirements of the mission. It is the simplest option. There is no need for cooperation or standardization. It eliminates scheduling issues occurring when several satellites have to share the same link. Finally, it is close to the surface of Mars.

However, there are many drawbacks. First, for an increased number of missions, the cost of sending an orbiter for each mission is significant. Second, one orbiter does not ensure a complete coverage of the planet. As the orbiter is orbiting, the communication with Earth is not continuous, the link is broken when the satellite flies over the hidden face of Mars. Third, it does not offer any flexibility as there is only one orbiter [6]. Last but not least, if either the lander or the orbiter fails, then the entire mission is lost. An example is the loss of Mars Climate Orbiter. It was expected to provide a communication relay for the Mars Polar Lander. As Mars Climate Orbiter failed, the Mars Polar Lander had to find other communication back-ups, before it failed shortly after [42]. These drawbacks justify the need for a permanent mission-independent communication architecture.

Previously, every mission had its own orbiter. Since the launch of Mars Odyssey in 2001 by NASA, Mars Express in 2003 by ESA and Mars Reconnaissance Orbiter in 2005 by NASA, NASA takes the most of the presence of this network of Martian orbiters to serve as relays for its robotic missions. It started with the two rovers Opportunity and Curiosity, then the Phoenix lander, the Mars Science Laboratory, and now InSight [43]. That way, NASA saves the cost of adding another orbiter for each mission. This is a first initiative of a permanent architecture around Mars. The network counts six orbiters up to date. It has been completed by the Indian mission Mangalyan and the NASA MAVEN in 2013. The joined mission ExoMars by ESA and Roscosmos has been added in 2016.

2.3.2 Martian constellations

The second concept is similar to the network space agencies are currently building around Mars with the different orbiters: the constellations around Mars. The class composed by the constellations is very broad. Some constellations are designed on the model of geosynchronous satellites and Earth, they are called areosynchronous constellations. Some constellations are designed to maximize the surface covered at all times or over one Martian days. This is the case of the Draim constellation. It covers all the surface of the planet with only four satellites. Others are made to cover some areas of interest such as the equatorial regions or the solar regions. This is the case of the 4retro111 constellation designed by JPL or the Flower constellations proposed by Sanctis [44].

The point with constellations is that their design is often limited to circular orbits whereas the design space is huge. Each orbit is characterized by six orbital elements that vary continuously. The number of satellites can vary as well as the number of planes, the number of satellites by plane, the inclination of the planes, the eccentricity of the orbit, the altitude of the satellites and so on. A very few examples are provided in Table 2.2 to show the diversity of concepts.

Even though it requires constellation management and operations, a constellation pro-

Table 2.2: Characteristics of several constellation design propositions

	MarsWeb	**Talbot-Stern**	**4retro111**	**Flower Mars DoubleR**
Reference	[45]	[46]	[42]	[44]
Number of satellites	6	20	6	6
Number of planes	2	5	6	6
Number of satellites per plane	3	4	1	1
Inclination (deg.)	37	59.55	172 (2) 111 (4)	88.1 (2) 49.2 (4)
Semimajor axis (km)	17,030	21,220	4189.92	4130
Redundancy	1 additional satellite in each plane	Each point covered by 4 satellites		
Navigation	No	Yes	No	No

vides some flexibility. Redundancy is ensured by adding only one satellite if the constellation is homogeneous. This increases the lifetime of the system. Because of the number of satellites in a constellation, this concept generally performs well in terms of coverage, either in global coverage of the surface, or in coverage of a specific area. It is probably the best option to ensure a full coverage of the Red planet at all times. The satellites are close to Mars which enables a good precision and a low power required for communications in the vicinity of Mars. Also, the constellation could provide other services such as navigation. Finally, with the development of low-cost satellites this option could become the cheapest.

However, there are several drawbacks to Martian constellations. First, it does not overcome the problem of solar conjunction. The communication link cannot be ensured at all times without a relay. The higher number of elements compared to other concepts can be a drawback because of the cost. The deployment can also be a concern in terms of cost and operations.

Inside the class of constellations, some general trends can be identified:

- Higher inclination of the orbit implies higher latitudes covered. Highly inclined orbits are required in order to cover the poles.

- Higher altitude implies a larger surface covered by each satellite and thus a better coverage with the same number of satellites. However, the higher the altitude is, the lower the accuracy. [6].

- A choice has to be made between a homogeneous constellation (all the satellites are the same) and an heterogeneous constellation. Homogeneous constellations are easier to set up as all the satellites are the same. In case of a failure of one of the satellites, the later can be replaced by any other satellite. It is more suitable for reconfiguration. Also, manufacturing price is lower. However, heterogeneous constellations provide more flexibility and often enable the same performance with a fewer satellites. Consequently, the total mass of the system is less.

- A communication constellation could also be used for navigation purpose. In order to have a position in three dimensions with the time, each point of the planet has to be covered by at least four satellites. Draim demonstrated that the minimum number of satellites required for such purpose is ten [46].

2.3.3 Satellites in heliocentric orbit

The last class of concepts is composed of satellites in heliocentric orbit. This class is the broadest one. It can be divided into two main categories: the spacecraft at Lagrangian points and the spacecraft in heliocentric orbit used as communication relays.

The architectures of this class of concepts have two main advantages. The number of satellites is limited to one or two. The link availability is always ensured as the satellites are not too close to Mars.

Lagrangian points

The Lagrangian points are points in circular orbit around the Sun but fixed in the Sun-centered referential whose first direction is defined by the axis Sun-Planet when considering a three-body problem composed of the Sun, a planet and a spacecraft. We assume that the other celestial bodies do not change the dynamic of the system. The mass of the spacecraft is small compared to the mass of the planet and to the mass of the Sun, thus it is negligible. This simplification of the three-body problem is referred to as the restricted three-body problem. Finally, the distance between the Sun and the planet is assumed to be constant. This approximation is valid for all the planets of the solar system except Pluto due to its orbit eccentricity. Such a problem is referred to as a circular restricted three-body problem. Under these assumptions, Lagrange has demonstrated that the problem has five equilibrium points called Lagrangian points referred as L_1, L_2, L_3, L_4 and L_5. L_1, L_2 and L_3 are located on the line passing through the Sun and the planet, as illustrated on Figure 2.8. They are unstable. L_4 and L_5 form an equilateral triangle with the Sun and Mars. They are stable [28, 47]. In the context of the designing a communication system between the Earth and Mars, only the Lagrangian points of the Sun-Earth system and the Sun-Mars system are considered. Several architectures have been designed using those points. Communication satellites are put in orbit around those points. Generally, the point L_3 is not used because of its instability and its distance from the planet.

The additional advantages of the Lagrangian spacecraft are that they are located at equilibrium points. The station-keeping required to maintain the spacecraft at its location is almost null, in particular at stable points, enabling a longer lifetime at the same cost as the spacecraft does not require significant amount of propellant. The setback of the stability is that there are others objects at stable points that could collide with the spacecraft and cause its destruction. Another advantage is that a spacecraft at L_1 or L_4 generally covers half of the surface of the planet. Adding the symmetrical L_2 or L_5 enables a coverage of more than 90% with only two satellites. The main disadvantage of this configuration is the distance from Mars.

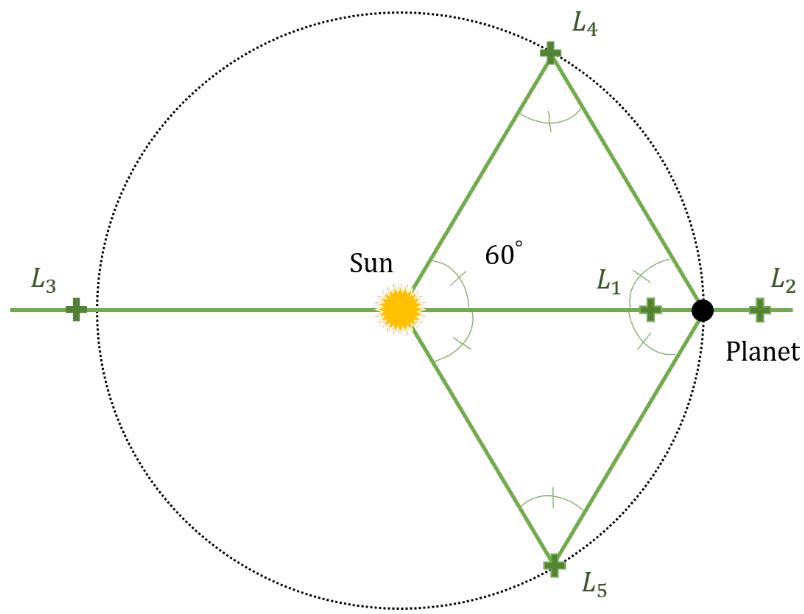


Figure 2.8: Lagrange points in a Sun-Planet system

Relays

A relay is a system composed of one or two satellites. Its purpose is to ensure the communication link between the Earth and Mars at all times, to solve the problem of the solar conjunction. Usually it is combined with a constellation around Mars that ensure the coverage of the planet. When the relay is combined with a constellation and thus used during only a few weeks over the synodic period, its cost has to be low compared to the overall cost of the mission. To satisfy these requirements (low-cost, relay during solar conjunction events), the orbit of the relay satellite is designed by taking into account three optimization parameters. The first parameter is the distance Mars-relay. As the relay is an add-on to the overall communication system (the Martian constellation), the Earth-Mars distance drives the system design. Assuming that the distance Earth-relay is of the same order of magnitude as the distance Earth-Mars, the distance Mars-relay has to be as small as possible to minimize the impact on the overall communication system design. The second parameter is the angle Mars-Earth-relay. As the relay is used during solar conjunction events, it has to be far enough from Mars to ensure the communication relay during those periods. As a result, a trade-off has to be made in term of distance. The satellite has to be as close as possible to Mars but far enough to overcome the solar conjunction issue. This trade-off is illustrated in Figure 2.9. Lastly, the third parameter is the stability of the orbit. The more stable the orbit is, the least propellant is needed to maintain the satellite on its orbit, and the cheapest the satellite is.

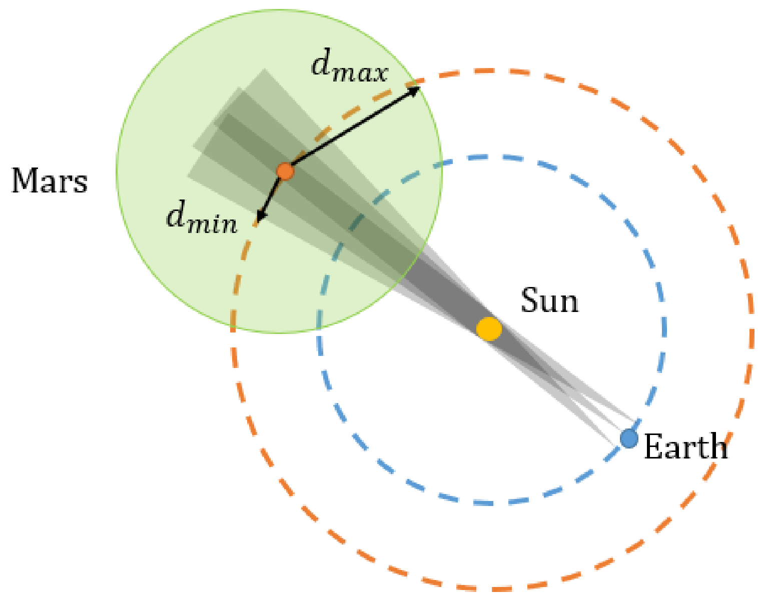


Figure 2.9: Trade-off between the minimum distance to overcome the solar conjunction issue (in grey) and to be close enough to Mars (in green) [48]

The relays are generally located either at Lagrangian points because of their stability or on Mars orbit, before or after Mars. Gangale orbits are orbits with the same properties as Mars orbit but inclined with respect to Mars orbit. They are also used to place one or two relays. Another option envisioned by Machuca Varela [49] is to use the manned transportation system on orbit around the Earth and Mars as a relay. This save the cost of an additional vehicle.

The point with the relays is that the performance depends on the location of the satellite, in particular the closeness to Mars. It performs average about the operation and the lifetime. The redundancy is easily ensured by placing the same satellite on the same orbit or at the symmetric location with respect to the Sun-Mars axis. The disadvantages are the need for station-keeping and the coverage that cannot be higher than 50% for one satellite.

Other concepts

A few other concepts exist. They are very specific and cannot be put into categories to assess their advantages and drawbacks. They are not included in this chapter but will be reviewed in the architecture survey presented in Chapter 6. These are:

- a relay on non-keplerian orbits,
- a twelve-satellite constellation around the Sun as required for FTL communications,
- a network of three satellites on Earth orbit,
- some so-called "mixed architectures" that are combinations of several other concepts,
- the use of the cycler transportation vehicle as a communication relay during solar conjunction events.

2.3.4 Summary

The existing communication architectures can mainly be broken down into four categories (if omitting the emerging heliocentric concepts that are not developed enough to be assessed and compared). The four categories are: the traditional solution (a lander with its dedicated orbiter), the Martian constellations, the satellites at Lagrangian points and the communication relays on heliocentric orbits. Within each category, different designs have been proposed by various authors. As seen before, there exist many possibilities within each category, leading to Observation 3.

OBSERVATION 3: The communication architecture design trade space is infinite.

High-level categories of concepts can be compared with respect to some high-level requirements such as coverage, link availability, redundancy or lifetime, as presented on

Table 2.3. From this figure, it is clear that there is no ideal solution. The main requirement being for the architecture to provide a reliable and continuous link between the Earth and Mars, a global coverage of the Red planet and a link available at all times is necessary. From Table 2.3, it can be seen that no solution provides both a good coverage and a good link availability. The implication is that an ideal solution is probably one that involves a combination of several architectures.

Table 2.3: Comparison between the different classes of communication architectures

	Traditional	Constellation	Halo	Relay
Coverage	Bad	Good	It depends on the configuration	Bad
Link availability	Bad	Bad	Good	Good
Distance from Mars	Good	Good	Bad	It depends on the configuration
Management and operations	Good	Bad	Average	Average
Redundancy	Bad	Good	Good	Average
Lifetime	Average	Good	It depends on the configuration	Average
Number of satellites	Good	It depends on the configuration	Good	Good
Station-keeping	Average	Bad	Good	Bad

Bad

It depends on the configuration

Average

Good

2.4 Methodological Gaps Identification

The Research Goal being to enable a reliable and continuous link between the Earth and Mars by designing a communication architecture, it is important to be able to determine the architecture that is the best suited to meet this goal. As seen in the previous section, the communication architecture design space is huge. A lot of concepts have already been proposed and analyzed. Different concepts have been created to answer different top-level requirements. For example, some architectures focus on the full availability of the communication link whereas others focus on the data rate. Some general trends between the requirements of interest and the concepts are underlined and summarized in Figure 2.3. Deeper comparisons have been carried out by different authors. The following sections review past architecture comparisons and highlight their limitations. In particular, four representative comparisons have been performed by Byford et al. [50], Breidenthal et al. [48], Baronio et al. [51], and Talbot-Stern [46].

2.4.1 Incompleteness of comparisons

As mentioned, the trade space is huge. There is no exhaustive list and description of all the existing concepts proposed to enable such a communication architecture between the Earth and Mars. As a result, it is almost impossible to compare all the proposed concepts. In the literature, two ways of comparing architectures can be identified: the comparison is made either between concepts of the same category, or between concepts from different categories. The categories are: Martian constellations, relay satellites and satellites at Lagragian points.

The first case is the comparison between concepts of the same category. For example, Byford and Breidenthal compare designs among the relay category. As a relay does not ensure a complete coverage of Mars, they both assume a constellation of satellites around Mars in addition to the relay. There are two problems with this approach. The first one is that the choice of the constellation around Mars is supposed to impact the relay chosen. This is because optimizing each sub-system is not equivalent to optimizing the global system. Hence, while the solution found for the relay may seem to be the best option, a better alternative may be found with another constellation. Talbot-Stern compares constellations around Mars. However, he considers different categories of constellations and then arbitrary chooses one of the constellation type to perform the optimization. He concludes saying that the constellation found is the best but if he had considered another type of constellations the results would have likely been different.

The second case is the comparison between concepts of different categories. An example is given by Baronio who compares three concepts:

- Two satellites at L_1 and L_2 Lagrangian points in the Mars-Sun system.
- Two satellites at L_1 and L_2 Lagrangian points in the Mars-Sun system coupled with a constellation around Mars.
- A constellation around Mars.

This approach presents various questionable assumptions. First, Baronio only considers three alternatives. Also, nothing proves that the concepts selected are the optimal in their own categories. For example, if the Martian constellation is poorly designed whereas the halo orbits are optimized, this may lead to choose the first option whereas the third one could be better if optimized. Lastly, Figure 2.3 illustrates the fact that each design performs better for a set of requirements so comparing one design per category may not be the right approach.

The inconsistencies presented here are further discussed in the following two sections. Overall, what can be concluded at that point is that all the comparisons that have been made are incomplete and present some gaps and fallacies

2.4.2 Uncertainty on requirements

As implied in the previous example of Baronio, the requirements drive the architecture design. Traditionally, the mission drives the communication payload design. In the present case, the desire is to provide a communication architecture suitable for all types of missions to Mars, both robotic and manned. As it has never been done before, there is no historical data for this type of problem that could be used as a baseline or a starting point. The model has to be built from scratch. This presents several challenges.

The first difficulty is that there is no common agreement on a set of requirements that such an architecture should meet. The goal is to provide a reliable and continuous communication link between the Earth and Mars. However, many different additional requirements can be derived from this. Among them, link availability, propagation delay, data rate, data volume, mass, size and volume, power required, or cost can be cited but there are not the only ones. The requirements are numerous and varied, they have to be prioritized. According to where the priority is put, the resulting architecture can be totally different. For example, Byford set the highest priority on availability, followed by cost, whereas Talbot-Stern focused on a design providing a navigation capability (ie. each point on the surface has to be covered by at least four satellites in order to have a position in three dimensions along with a time).

The second difficulty is that the definition of a same requirement can be very different from one study to another. Breidenthal and Baronio both set the highest priority on the data rate. However, the level that should be meet in Baronio's study is 500 kbps, whereas Breidenthal set the requirement from 10 Mbps to 250 Mbps. The two requirement's levels differ from more than one order of magnitude. Talbot-Stern set the level of the data rate requirement to 1 Mbps, whereas the data rate is not among the top-priority in his study. As a result, the range of values for a same requirement tends to be very large.

Lastly, there is a lack of quantification in some analysis. For example, Talbot-Stern's concept must ensure a "sufficient coverage". What does sufficient means: fifty percent, ninety percent or one hundred percent? What areas has to be prioritized? Usually the constellations around Mars cover the equatorial zone and tend to leave the polar regions. However, polar regions are areas of interest due to the presence of ice water. This requirement is not exploitable due to its fuzziness.

These observations lead to the identification of the first gap:

GAP 1: There is lack of proper requirements definition and analysis in the communication architecture studies that have been conducted in the past.

2.4.3 Discrepancy in the impact of a technology choice

Another issue that has been highlighted by the study of the four comparative analysis selected are the fuzziness in the communication technology capabilities. This is particularly true with optical telecommunications as the technology is still in a demonstration phase and has never been tested outside of the Earth's sphere of influence. The most direct example is with regards to the minimum $\widehat{SEM}$ value defined during solar conjunction events for the optical technology. The $\widehat{SEM}$ is defined in the previous chapter by Figure 1.4. Some authors assume that the minimum value of the $\widehat{SEM}$ can be as low as three degrees, as Breidenthal assumes in his paper. On the contrary, others such as Byford, state that the minimum value should be set at ten degrees and that manufacturers are not sure to be able to go below five degrees in the future. This difference leads to significant changes in the optimal location of a relay for example. Indeed, a difference of seven degrees can lead to a change in relay location of 45 million kilometers. As shown in Figure 2.10, if the angle in grey is equals to 3 degrees, then the distance a is about 40 million kilometers. If the angle in black is equal to 10 degrees, then the distance a is about 130 million kilometers. The difference between the two is about 90 million kilometers and leads to a change in the relay's location of 45 million kilometers.

This example is one among many. It leads to the identification of a second methodological gap:

GAP 2: Assumptions made on the capabilities of the technologies are inconsistent from one study to another.

2.4.4 Summary

From the analysis of four representative comparisons of Earth-Mars communication architectures performed by four different authors, we noticed two important methodological gaps. First, there is no agreement on a common set of requirements and there is no analysis

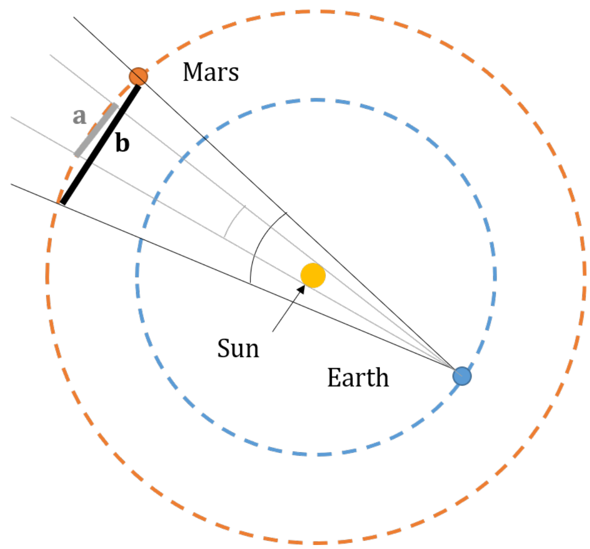


Figure 2.10: Impact of the modification of the minimum SEM angle on the location of a relay

of these requirements. Because requirements drive the design, this is analogous to comparing architectures that are not designed for the same purpose. Second, assumptions made on the communication system such as the performance in terms of solar exclusion angle differ from one study to another. Besides, as already mentioned, the comparison studies are incomplete because of the size of the trade space. Most of the time they are reduced to pairwise comparisons. This leads to the third gap:

GAP 3: Architecture comparisons are inconsistent and/or incomplete.

To achieve the research goal, which is to enable a continuous and reliable communications between the Earth and Mars through the design of a permanent architecture, those gaps need to be overcome to be able to rank and compare the architectures in a cogent way. This defines the overarching research objective of this thesis.

OVERARCHING RESEARCH OBJECTIVE: Develop a methodology that enables relevant and consistent comparisons of Earth-Mars communication architectures and supports gap analysis.

CHAPTER 3
PROBLEM DEFINITION

In the previous chapter, the state-of-the-art of the communication technologies and the architectures needed to meet the research goal was discussed. In this chapter, this Research Objective is decomposed into several Research Questions. For each research question, the techniques or tools available to answer the question are presented and discussed. The most appropriate and relevant one is selected and hypotheses are formulated to address each question. Some validation criteria are also established to validate each hypothesis at the end of the work.

3.1 Research Scope

Before deriving the research questions, the scope of the study has to be narrowed and explained. The restriction of scope impacts some choices about the requirements for example.

3.1.1 Conceptual design

The traditional design process of engineering systems is composed of four main phases [52, 53]:

- Phase 0: Specification of information – Before starting the design of a product, it is necessary to clarify what is required for the product. This task of clarification is about gathering and analyzing the requirements that have to be fulfilled by the product, as well as the existing constraints on the design of the product. The market and the desires expressed by the stakeholders have to be understood and translated into requirements.
- Phase 1: Conceptual design – The end goal of this phase is to come up with a first

feasible and viable design. From there, the goal is achieved by selecting a set of requirements that drive the design, performing trade studies between possible designs and making the main design choices. An initial design is proposed based on background knowledge and results from trade studies.

- Phase 2: Embodiment (or Preliminary) design – At the end of this step, most of the design is fixed. The initial concept has been transformed into a product that will be later manufactured and operated. The design is sufficiently detailed to be evaluated against the requirements and the customer needs.

- Phase 3: Detailed design – During this phase, the end-product is designed and tested. Features are perfected. Final decisions about the arrangement, forms, dimensions, material properties etc are made. Ultimately, a prototype is built and tested.

The legs of each phase are detailed in Figure 3.1. The process is iterative. The design process leads to the fabrication of the system at the end of the detailed design phase.

In the context of this study, the focus is on the phase 1, the conceptual design stage. More precisely, it is initiated with a list of potential requirements on the architectures identified from the literature. These requirements are mapped against the architecture and the technology. The process ends with the "best" architecture for the set of requirements selected. The choice of staying at the conceptual stage impacts the methodology proposed and the type of requirements considered in the study.

3.1.2 Communication-centered analysis

There are three main approaches to decompose a system [54]:

- Operational decomposition: the system is viewed through the eyes of the stakeholders. The system is decomposed according to different operational elements such as operational needs, operational sequences, the operational environment, operational constraints, user and maintainer roles and so on.

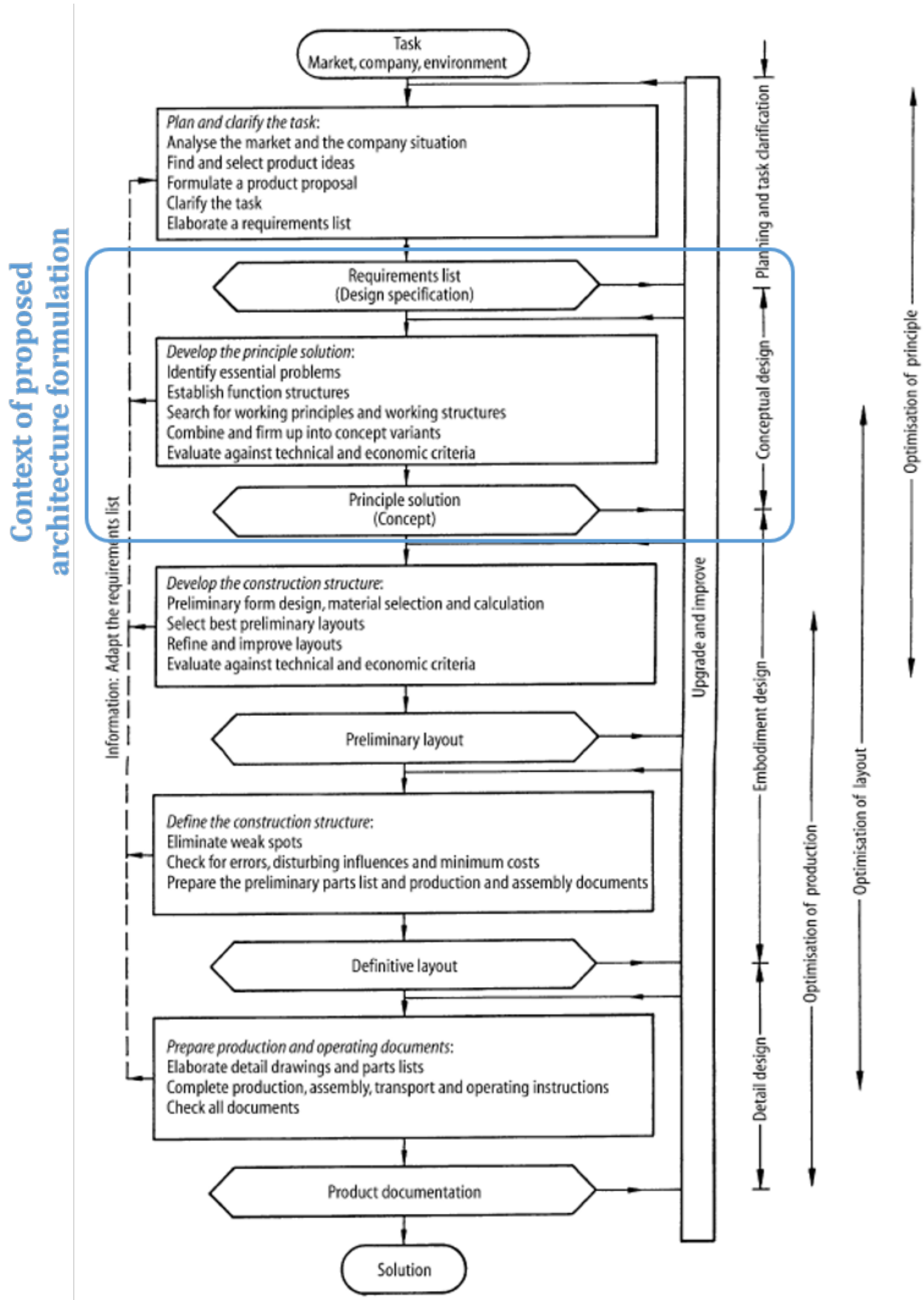


Figure 3.1: Illustration of the design process [52]

- Functional decomposition: the system is viewed through the question "What" should be performed by the system to meet the requirements. The system is decomposed according to its features.

- Physical decomposition: the system is viewed through the question "How" is it built. The system is decomposed according to its different parts and sub-systems.

In this study, the focus is on the communication capability. As a result, the decomposition chosen is a functional decomposition and the focus is solely on the main function that is the communication. This reduces the parts of the system considered. For example, propulsion is not considered. The number of interactions is reduced to the interactions between the subsystems that contribute to the communication function. There is no study of inter-functional relationships. This widely reduces the problem, the number of requirements and system's elements considered.

3.1.3 Existing technologies

Regarding communication technologies and other technologies that could be considered in this study, two approaches are possible:

- Setting the requirements and assessing the architectures that are able to meet these requirements. If none, quantifying the improvements needed on existing technologies to meet the target.

- Evaluating the different architectures with available telecommunication technologies and see how well each architecture performs. In that case, the solution may imply an unfeasible number of satellites for example. Then, trade-offs have to be made to reach a feasible solution.

In the first case, the architectures are fixed and the technologies have to fill the gap between the actual and the expected performance. In the second case, we play with existing

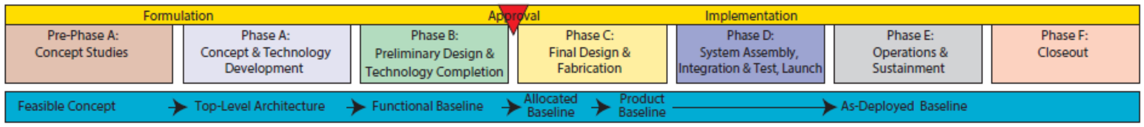


Figure 3.2: NASA Project Life Cycle Process Flow [55]

technologies and the architectures have to be modified to meet the requirements. This is the approach chosen. Hence, in this study, it is assumed that only current capabilities are available. In other words, it is about assessing how well the system can do with existing technologies.

3.1.4 Operation phase

The life cycle of a space project is divided into seven phases defined by NASA [55] (Figure 3.2). The first four phases correspond to the phases of the design process of engineering systems as already described. All the phases are detailed in Table 3.1. The study performed here is located at Phase A and it only takes into account the operation phase (Phase E) in terms of requirements and operations. Consequently, the maneuvers required to put the satellites into their orbits and to withdraw them are not taken into account. The extent of the study has been framed in order to better define the research area tackled.

3.1.5 Radiofrequency

As depicted in the "Background" Chapter, it is very likely that the technology used for deep-space communications in the following year will be an hybrid combination of radiofrequency and optical communications. The purpose of this thesis is to demonstrate a methodology enabling relevant comparisons of communication architectures. The focus is on the architecture and not on the technology. This is why the demonstration is limited to one technology, the radiofrequency. Later, this work could be extended by adding the optical communications and a hybrid combination of the two.

The radiofrequency is chosen to demonstrate the methodology as it is the most devel-

Table 3.1: Description of Project Life Cycle Phases by NASA [55]

Phase		Purpose	Typical Outcomes
Pre-Formulation	**Pre-Phase A** Concept Studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mock-ups
Formulation	**Phase A** Concept and Technology Development	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition
	Phase B Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mock-ups, trade study results, specification and interface documents, and prototypes
Implementation	**Phase C** Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D System Assembly, Integration and Test, Launch	To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
	Phase E Operations and Sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

oped technology to this point. Indeed, optical communications are still in the development phase. The capability has not been proven for communications with a celestrial body further than from the Moon. On the contrary, many historical data and models are available to predict the performance of radiofrequencies.

Restraining the study to the architecture enables to stay at a higher lever of definition of the architectures. All the implementation of the characteristics of the communication technology is not required. When the characteristics of the technology are needed, the X-band is chosen as a reference.

3.2 Decomposition of the objective

The scope of the study is set. In the following, the research objective is broken down into several research questions. The goal of this study is to build a methodology to enable relevant and consistent comparisons of Earth-Mars communication architectures. To do so, several obstacles corresponding to the methodological gaps identified in the previous chapter have to be overcome.

The first gaps tackles the lack of definition of the requirements. To perform a relevant comparison between several architectures, a set of requirements corresponding to a need has to be established. Once this set is defined, the problem is that there are some interactions within the communication system, as illustrated in the previous chapter on Figure 2.1. The protocol has been excluded. The focus is on the architecture and the interaction between the architecture and the communication technology. The reduced problem is depicted on Figure 3.3. We want to know the impacts of the requirements on the architecture, taking into account the interactions with the technology. The impacts are represented in blue on the figure. The relations that are of interest in this study are represented in red on the figure, that is to say the impact of the technology on the architecture and the impact of the requirements on the architecture. However, as the requirements impact the technology and then the technology impacts the architecture, by transitivity the requirements impact

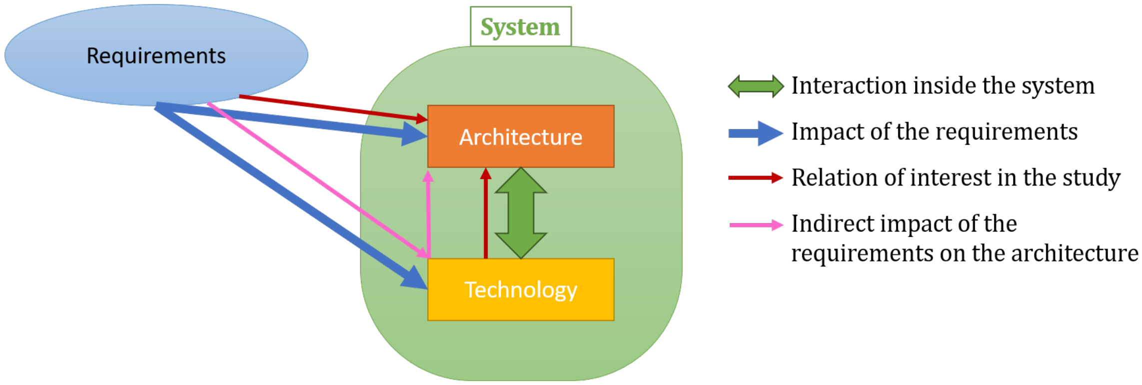


Figure 3.3: Schema of the reduced problem

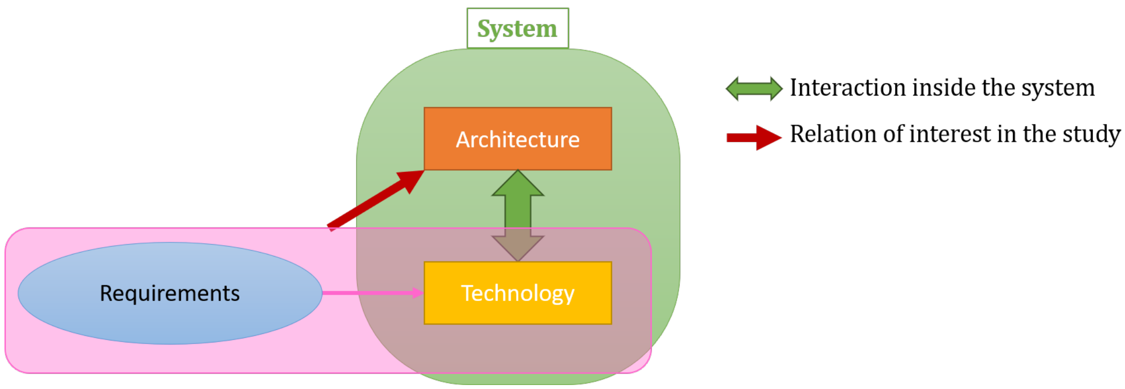


Figure 3.4: The new representation of the problem after mapping of the requirements

the architecture following the pink arrows on the figure. This path also has to be considered. A technique is necessary to organize the requirements and to emphasize their impacts on both the architecture and the technology. This leads to the first research question.

RESEARCH QUESTION 1: What process enables the mapping between requirements and the communication system?

The goal of this first research question is to simplify the problem. The requirements are mapped against the system. The simplification is illustrated on Figure 3.4 in pink.

Once the requirements are established and organized, the focus is on the architecture. The objective is to offer a methodology enabling relevant comparisons. A necessary condition is to base the comparisons on the same assumptions and to implement and evaluate all the architectures the same way. This leads to the second research question.

RESEARCH QUESTION 2: How to assess the communication architectures so that they can be consistently and rigorously compared?

The framework designed as an answer to the research question 2 enables the implementation and the evaluation of the architectures with respect to the set of requirements previously defined. The end-goal of the methodology proposed in this thesis is to be able to determined what is the "best" architecture for a set of chosen requirements. Thus, the last research question is focused on a technique to rank the alternatives. This leads to the research question 3.

RESEARCH QUESTION 3: How can communication architectures be consistently ranked?

The three research questions break down the research objective into three distinct parts. For each research question a review of different tools or processes that could be used to answer the question are presented. For each question, a hypothesis and some validation criteria are proposed.

The basis of a relevant comparison is a set of criteria against whom the alternatives can be evaluated. This calls the first research question: "What process enables the mapping between requirements and the communication system?"

3.3 The requirements

This section details the study of the requirements needed and offers a hypothesis to answer the first research question.

3.3.1 Requirements definition

Before selecting the best process to map the requirements against the communication system, the requirements have to be defined. The communication system has been introduced in the "Background" Chapter and the scope reduced in the previous section.

According to INCOSE, a requirement is "a statement that identifies a system, product or process' characteristic or constraint, which is unambiguous, clear, unique, consistent, stand-alone (not grouped), and verifiable, and is deemed necessary for stakeholder acceptability" [56]. Common practices to gather requirements include interviews, surveys, wants and needs analysis or focus groups [57]. In the present case, the customers are the national or international space agencies and potentially some private companies. The system is not designed yet and we do not have the possibility to carry out survey or to meet the stakeholders. As a result, the requirements are taken from the literature written by potential customers and/or stakeholders (space agencies such as ESA or NASA). While gaps exist regarding the prioritization of high-level requirements and the level of each requirement, there is a common agreement as to the nature of top-level requirements. The first step of the thesis is to define the requirements.

The number of requirements considered in this study is intentionally limited. The reasons are the following.

1. With a limited number of requirements, the essence of the system can be captured. The system has to be as flexible as possible.

2. Each additional requirement adds a new dimension to the problem. The more requirements there are, the more constraints there will be on the design space and the more difficult it will be to meet the objective of the study.

3. The human brain can only deal with a limited number of information. A limited number of requirements enables a person to grab the main points of the design constraints whereas an overwhelming number of requirements would muddy the waters.

4. A limited number of requirements is easier to trace back from technologies and architecture decisions

3.3.2 Mapping techniques

Once the requirements are defined, one needs to map them to the communication system. This section reviews existing mapping techniques in order to identify the ones that can be used or modified to build the pink block in Figure 3.4. Before reviewing the existing techniques, the criteria that have to be satisfied by the chosen technique are outlined.

Requirements impact the whole system. The communication technology, the architecture, but also the protocol and other sub-systems that are not considered in this study. The mapping technique has to identify the parts of the system that are impacted by a given requirement and offer a **classification** of the requirements based on their impacts.

The framework under consideration and development will eventually be used to support architecture comparisons and gap analysis, i.e the identification of the impact of a technology improvement or of a requirement relaxation on the architecture design space. Consequently, **traceability** between requirements and impacts on the architecture design space has to be guaranteed.

Finally, the set of requirements selected in this study is restricted. It could be extended in the future. The framework also aims at being generalizable and used for a more global interplanetary communication network not only restricted to Mars. Consequently, the technique has to enable a **structured and systematic framework** to organize the requirements and allow for potential expansions. The final constraint is that the technique has to be **transparent**.

Several techniques, methodologies and processes for requirements classification and mapping are reviewed and discussed below.

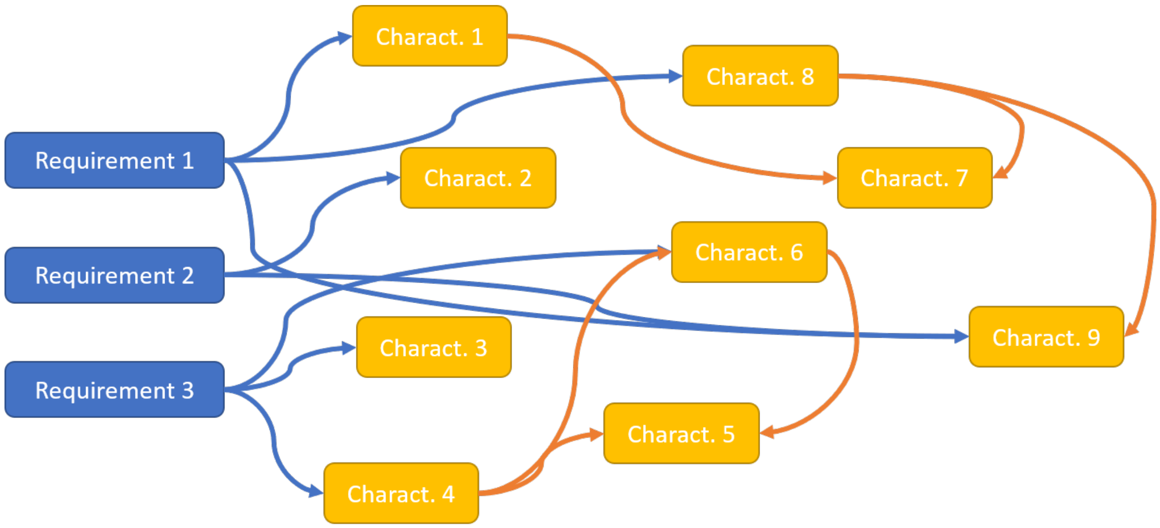


Figure 3.5: Illustration of an interrelationship diagraph

Interrelationship Diagraph

The interrelation diagraph is a graphical tool used to determine the importance of the design characteristics by drawing lines of causes and effects. It starts with one central issue and maps out the links among the related ideas. It focuses on the process, reveals the issues in those processes and highlights the main drivers [58]. In the present case, the central issue is one requirement and the related ideas are the system characteristics. The process is repeated for each requirement, as illustrated in Figure 3.5. The benefit of this technique is that it actually links requirements to technologies in a very simple way. The number of links also establishes a hierarchy in the requirements and the traceability is ensured. The drawbacks are that the resulting diagram is not organized. It does not enable any classification or quantitative relationships.

Relationship Matrix

The relationship matrix is a matrix linking two elements: the "Whats", listed on the left, that constitute the lines of the matrix, and the "Hows", listed on the top, that constitute the column of the matrix. In the present case, the "Whats" are the requirements and the "Hows" are the system capabilities. The matrix assesses qualitatively the relationships between the requirements and the technologies. Usually the scale is a low-medium-high scale translated into a quantitative one using the scale 1-3-9. Its assets are to be very simple and structured, and to establish the link we are looking for.

Quality Function Deployment (QFD)

The Quality Function Deployment is a more complex technique compared to the previous ones. It is a system engineering process initially developed by the Japanese automobile industry in the 1970s. It establishes a qualitative link between the customer needs/requirements and key process variables/design characteristics. It is an upgraded version of the Relationship Matrix. The QFD interest lies in the fact that customer requirements cannot be easily manipulated whereas the design characteristics can be. Its purpose is to understand the impact on downstream processes. It identifies the most important product and process characteristics. The QFD has been demonstrated in many domains including Manufacturing Process Improvements and the Joint Strike Fighter, and for various goals such as identifying market needs, product developments or strategic planning and management. The QFD is a set of one or several matrices. It has the advantage of being highly visual because of its matrix form as well as its waterfall structure. Indeed, the QFD starts off with a first top-level matrix with creates the first link between the customer requirements (the "Whats") and the design characteristics (the "Hows"), just as the relationship matrix. Then, those "Hows" become the "Whats" as the study continue down to the lowest levels to the Key Process Variables. The different elements of a QFD matrix are explained on Figure 3.6. The cascade of several matrices is illustrated Figure 3.7. This process allows to quickly identify whether a customer requirement was missed or failed to be answered (traceability). It provides a good environment to structure the information and provides both qualitative and quantitative information. One of the drawbacks of the QFD is that there is no classification of the information [59, 58]. It is also more complex that the interrelationship diagram and the relationship matrix.

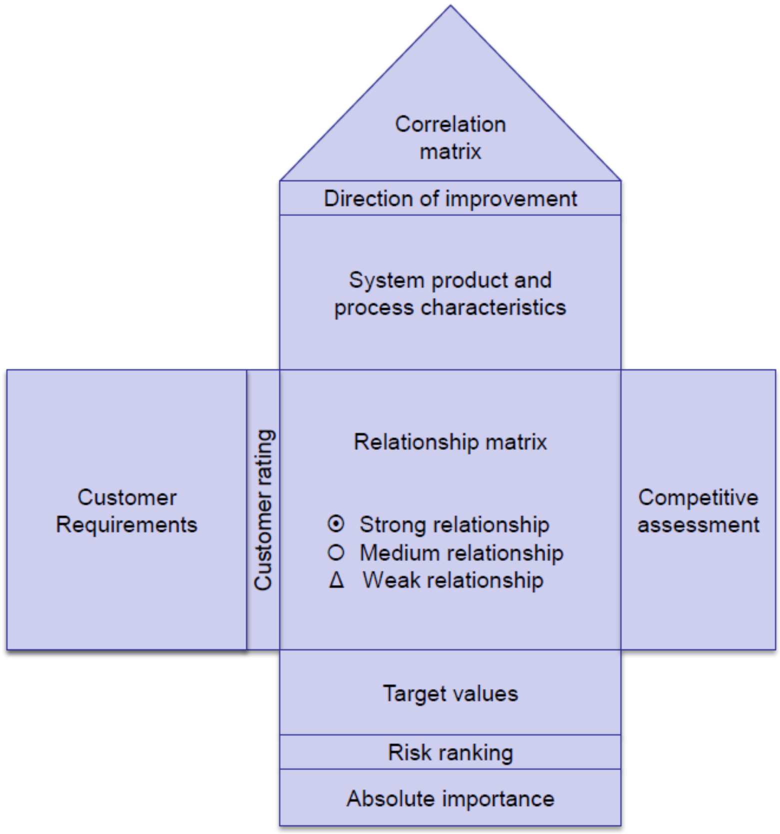


Figure 3.6: Elements of a QFD matrix [58]

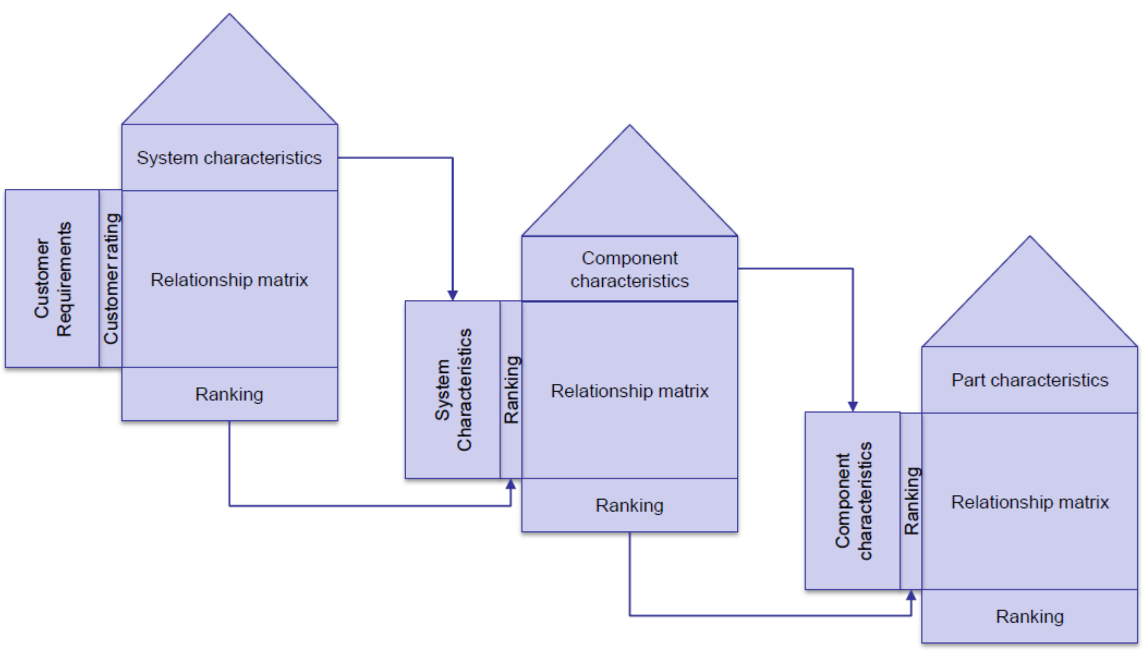


Figure 3.7: Cascading process of a QFD [58]

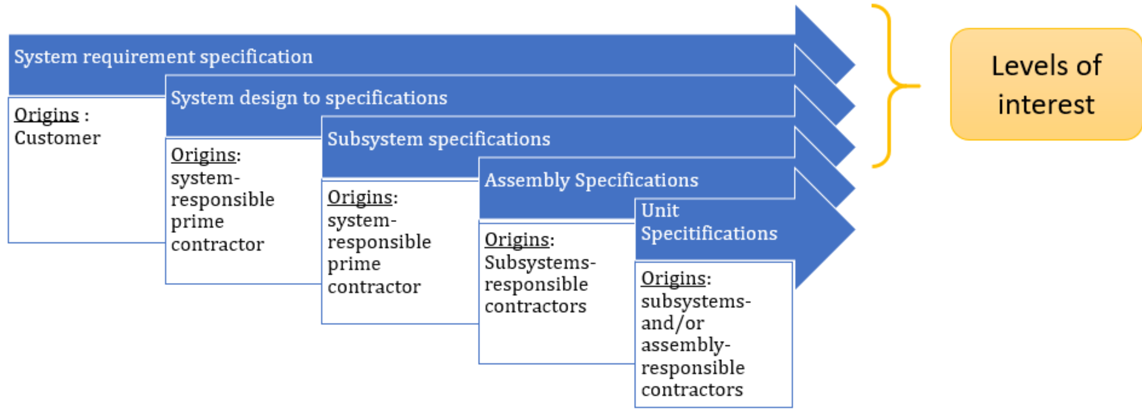


Figure 3.8: Decomposition view for a specification tree

Specification Tree

A specification tree reveals all the technical standards of a system which is being developed in a hierarchical order. For complex aerospace systems, it goes from the systems-of-systems requirements all the way down to the unit specification, including system design to specification, subsystem specifications and assembly specifications. When the systems-of-systems requirements are generated by the customers, the lower levels are often derived from the systems or subsystems themselves. This process is illustrated in Figure 3.8. Specification trees are useful for decomposing and tracking requirements and dependencies. Used in parallel with evaluation metrics, they reveal the system compliance level. It flags risk areas early, prepares for the system qualification and characterizes the deviations quantitatively and qualitatively [58]. Specific to that study, Figure 3.9 illustrates the link between requirements, technologies and architecture and the kind of specification tree that needs to be found. The requirement level 0 corresponds to the continuous communication between Earth and Mars. The goal of the study is to be able to find the best architecture that can fulfill the main requirement, in other words finding the right set of technologies. This high-level requirement is divided into lower levels of requirements. On Figure 3.9, two levels of decomposition are illustrated but there can be more sub-levels. Those sub-requirements correspond to existing technologies or technologies under development that

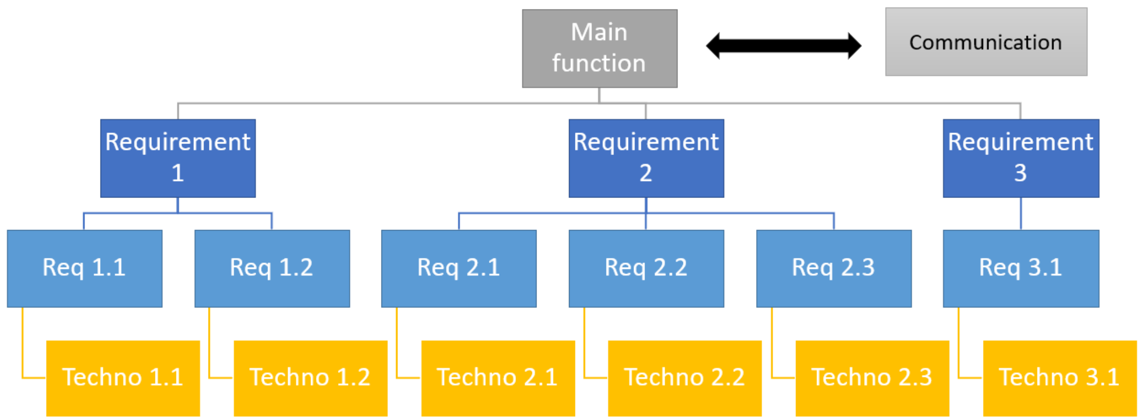


Figure 3.9: Illustration of a specification tree

the decision-makers need to choose from. The advantage of the specification tree is that is enable requirements decomposition and traceability. It is also structured and enables traceability. However, it is more complex than an interrelationship diagraph or a relationship matrix.

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process was developed by Thomas L. Saaty in the 1970s. The term "Hierarchy" is important as it allows for more than a single layer of criteria. It is useful for many applications like project planning, priority determination, selection of alternatives and resource allocation. It is particularly capable when trying to compare solutions that are fundamentally different, for example airplanes and satellites as illustrated on Figure 3.10. Because aircraft and satellites cannot be properly compared directly, a higher level needs to be reached, where both alternatives can be properly scored on the same scale, and thus compared. The AHP is composed of four steps. The first step consists in establishing the hierarchy. There are three levels as illustrated on Figure 3.11. The highest level is the final decision. In the case of a requirement mapping, the final decision is equivalent to the main function of the system, that is to say "Communication". The second level is the criteria, in our case the criteria are the requirements. The third level is the alternatives, in our case

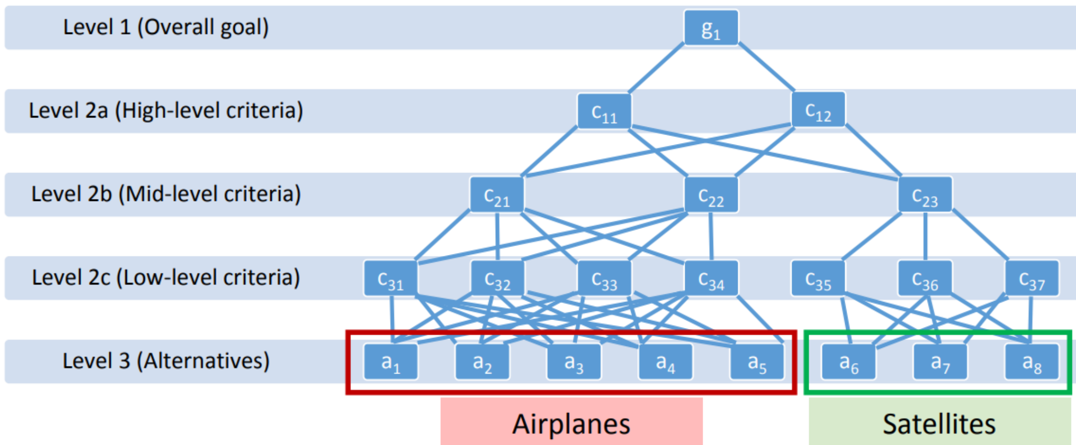


Figure 3.10: Analytic Hierarchy Process example on a comparison between satellites and airplanes [58]

the system capabilities. The structure is similar to the one of the specification tree except that the requirements account for one level only in the present case and that the emphasis is on establishing a ranking instead of a structure. Here, all the system characteristics are put under each requirement and their scores indicate the level of link. The second and the third steps rely on prioritization matrices. The prioritization matrix is explained on Figure 3.12 for the requirements. The scales used to rank can vary but are usually 1-3-9, or 1 to 9. The establishment of the matrix is the second step of the process. Then, the third step is to build one prioritization matrix per requirement comparing the system characteristics against themselves for each requirement [58]. AHP is used to obtain requirement relative importance, and then the system characteristic relative importance for each requirement as illustrated on Figure 3.13. The advantages are that this technique is structured and supports decision-making. However, it is not very simple neither transparent.

The envisioned techniques are summarized and compared with respect to the criteria previously defined, in Table 3.2.

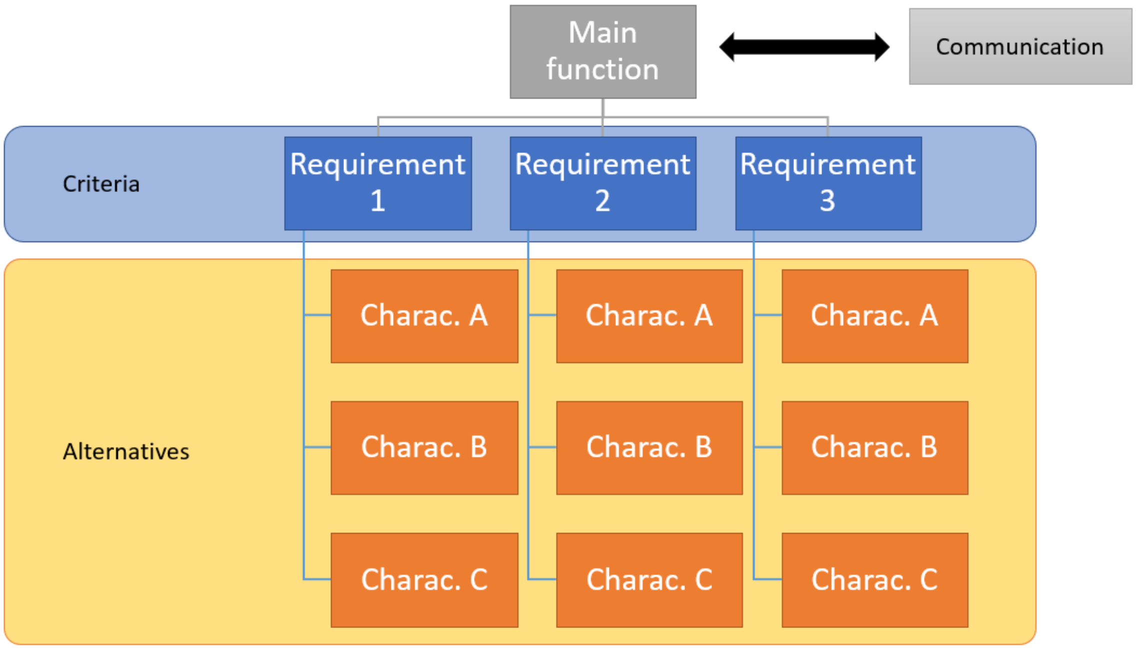


Figure 3.11: First Step of AHP: Defining criteria and alternatives

Table 3.2: Comparison between the different requirements mapping techniques

	Classification	Structured	Simplicity	Transparency	Traceability
Interrelationship Diagraph	Red	Red	Green	Yellow	Green
Relationship Matrix	Red	Green	Green	Green	Green
QFD	Red	Green	Yellow	Green	Green
Specification Tree	Red	Green	Yellow	Green	Green
AHP	Red	Green	Red	Red	Green

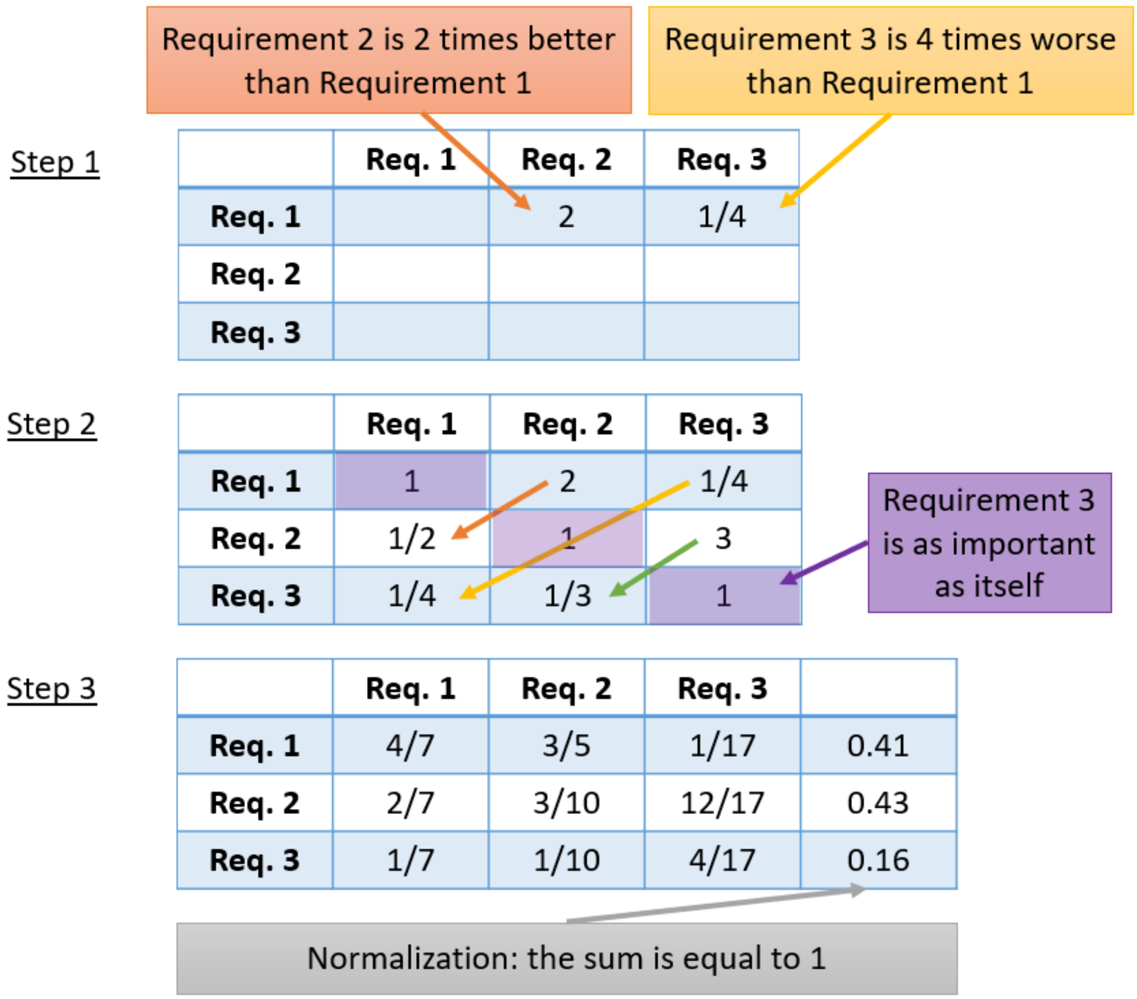


Figure 3.12: Second step of AHP: the prioritization matrix for the requirements

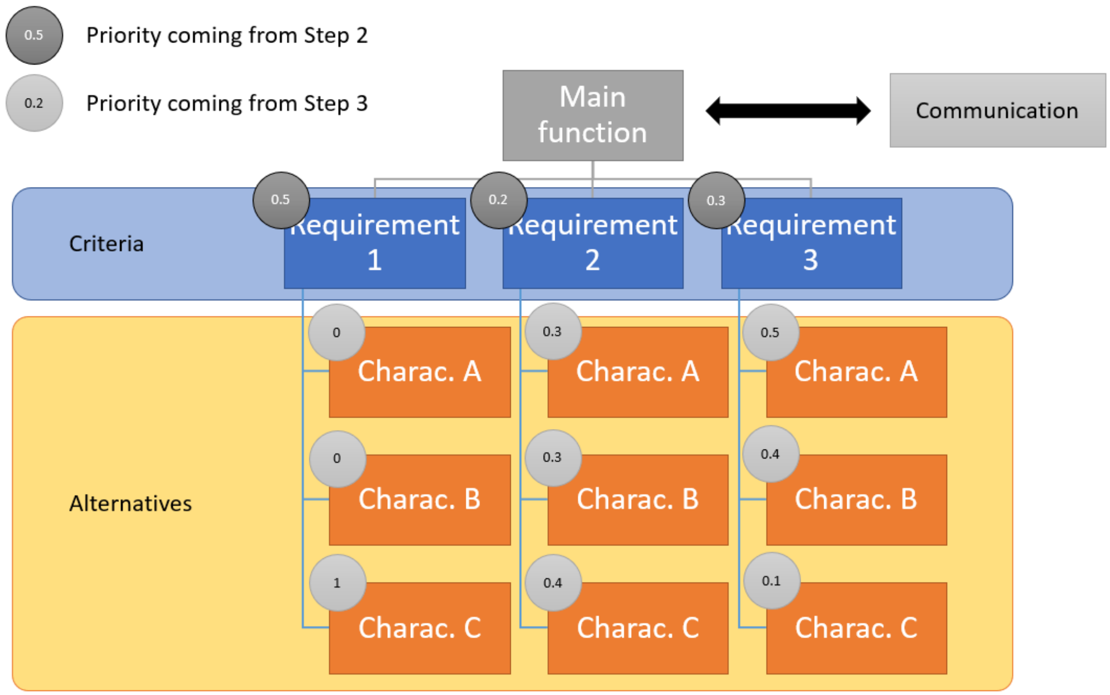


Figure 3.13: Final step of AHP: the results

3.3.3 Hypothesis

From Figure 3.2, the best technique to meet our objective is the relationship matrix. However, like all the other techniques envisioned, it does not enable a classification of the requirements. As seen on Figure 3.3, the requirements impact both the architecture and the technology and consequently these two different impacts need to be captured. Thus, an additional step is added before using the relationship matrix. A common method to classify the requirements is to use a taxonomy. A taxonomy enables an efficient and logical organization of the requirements. It performs two activities:

1. regrouping the requirements in different groups, and

2. creating relationships between the different groups to translate the interactions between the groups.

Three properties define a good taxonomy: completeness, perceptual orthogonality (or mutual exclusiveness) and parallel structure [60].

- Completeness means that the taxonomy encompasses all the requirements considered for the system. The set of requirements selected must provide an overall comprehensive understanding of the system and describe it entirely.

- Mutual exclusiveness implies that the requirements have to be classified in independent categories called taxons. Perfect orthogonality is most likely to be impossible. Some requirements will appear in several taxons. To overcome this issue, links have to be created between the taxons that have common requirements so that a modification in one taxon impacts the other taxons in a cogent way.

- Parallel structure and uniformity refer to the different levels in the taxon. The taxon starts with a top-level requirement and can spread on different levels of requirements. A parallel decomposition of the taxon has to be ensured.

Many taxonomies exist and are described by Dufresne [60]. In the present study, what is interesting is the impact of a given requirement on the technology, the architecture or both. As a result, the requirements will be divided into two categories:

- the requirements that impact the communication technology, and

- the requirements that impact the architecture.

Once these two categories are developed, the relationship matrix is filled, isolating the impacts on the technology to the impacts on the architecture.

HYPOTHESIS 1: *If* a relationship matrix is developed *then* the requirements are mapped appropriately against the communication system.

In order to verify the Hypothesis 1, Experiment 1 is performed. First, the requirements are divided in the two taxons: the requirements impacting the technologies and the requirements impacting the architecture. Second, the relationship matrix is established. The verification criteria for the hypothesis are the following:

1. Are all the requirements taken into account in the relationship matrix?
2. Does the relationship matrix enable a classification of the requirements according to their impacts on the communication system?
3. Does the relationship matrix make explicit the links between the requirements and the system?

Once the mapping between the requirements and the system has been established, the architectures are ready to be implemented. This calls the second research question: "How to assess the communication architectures so that they can be consistently and rigorously compared?"

3.4 Implementation of the architectures

This section discusses the way to implement the architectures and offers a hypothesis to answer the second research question.

3.4.1 A physics-based approach

Overall, there are two approaches to model a system: an empirical approach and a theoretical (also referred as to physics-based) approach. In both cases, the quantitative relationship is a mathematical function that links the inputs to the outputs. In this study, the inputs refer to the requirements whereas the outputs refer to the design f the architectures.

Empirical approach

The empirical approach is based on the experience and on experiments. Empirical relationships between the inputs and the outputs are derived from historical data. According to Adrianus Dingeman De Groot, the design of an empirical relationship is based on a cycle of five steps [61].

1. Observation: the observation of a phenomenon

2. Induction: the formulation of a generalized hypothesis to explain the phenomenon, the hypothesis being a mathematical relationship

3. Deduction: the formulation of experiments to verify the hypothesis

4. Testing: the realization of the experiments to collect data

5. Evaluation: the verification of the results from the experiments against the hypothesis to verify the hypothesis.

Common empirical relationships are linear regressions performed on a set of data from experiments. This approach is appropriate when results from experiments are available and when the concept studied falls in the range of what already exists. If it is outside this range, the accuracy of the relationship is questionable. In that case, the solution is to turn towards a theoretical approach and the design of physics-based analytical models.

Theoretical approach

Contrary to empirical models using rule-based or data-driven models to derive the relationships to represent the behavior of the system, physics-based models rely on physics principles and engineering models. Kakadiaris defines physics-based models as "a mathematical representation of an object (or its behavior) which incorporates physical characteristics such as forces, torques and energies into the model, allowing numerical simulation of its behaviors" [62].

In the context of the present problem, there is no historical data available as no such an architecture currently exists. Empirical relationships could be extrapolated from data from previous and current missions to Mars, but nothing ensures that the extrapolation is justified and works in our context. As a result, a **physics-based modeling and simulation environment** is required.

3.4.2 Hypothesis

To implement the architectures the same way based on the same assumptions, a framework applicable to all the architectures is required. This framework has to be designed in a physics-based modeling and simulation environment. Before selecting an environment, the capabilities needed have to be detailed.

The research goal is to enable communications between the Earth and Mars. The focus of the thesis is on the architecture and the interaction between the architecture and the communication technology. First, the framework has to have the capability of modeling an architecture of several satellites. This encompasses the capability of computing **trajectories** and propulsive maneuvers. As the architectures are around the Earth and Mars, the framework also has to support **interplanetary** missions.

Then, the architectures are communication architectures. The framework has to be able to provide an evaluation of an architecture against some high-level requirements regarding communications. Among those requirements, the link availability and the coverage are expected. The framework has to provide measures of **access** between elements, **coverage** of the surface of the planet and some computations of **distances**.

Third, the interactions between the technology and the architecture are studied. The framework has to have the capability of **implementing communication technologies**, from radiofrequencies to optical communications. The implementation encompasses the definition of the characteristics of antennas, receivers, transmitters and the settings of some parameters such as the solar exclusion angle. It has to provide **link budgets** to assess the quality of the communications.

The capacities described before correspond to the need for the special case tackled in the present thesis. This thesis is a demonstration of a framework. It has to be **extendable** to other capabilities that could be required to model the full communication technology and eventually the protocol. This ability to be extended has to be taken into account too.

HYPOTHESIS 2: *If* a framework in a modeling and simulation environment with the required capabilities is designed *then* the communication architectures can be evaluated.

In order to verify Hypothesis 2, Experiment 2 is performed. A metric is associated to each requirement to evaluate the architectures. The verification criteria are the following:

1. Is the framework applicable to all the architectures?

2. Is the framework able to assess an architecture with respect to all the requirements?

3. Is the process repeatable?

3.4.3 Modeling and simulation environments

To implement the framework, a modeling and simulation environment has to be selected for this thesis. The environment has to satisfy some criteria. The first criteria is to have the **capabilities** depicted previously.

Given the time constraint to accomplish the work described in this document, the environment has to be **available**. It also has to have been already tested. The results provided by the environment have to be validated. The results have to be always the same for the same simulation to ensure the repeatability of the process. The environment has to be **robust**.

Lastly, the implementation has to be as easy as possible. A good asset of the environment would be to be **user-friendly**. An additional constraint is that the environment has to be available to a non-US citizen. Three environments are considered in the following.

A new environment

This first option envisioned is the creation of a new environment. The advantage of this option is that all the capabilities can be implemented. The friendliness of the environment only relies on me. The environment can be publicly released at the end of the thesis and made available to anyone. As I implement the tool, I know exactly how it works and its capability. I do not rely on any technical support.

There are two main drawbacks to this solution. The first one is that the implementation is not validated. A lot of work has to be put in the implementation, the testing and the validation of the results produced by the environment. Second, the environment is not available. Given the constraints of time on this work, if this solution is chosen, a lot of effort could be allocated to the design of the environment whereas it is not the main goal of this study.

General Mission Analysis Tool (GMAT) by NASA

GMAT is an open source tool created by NASA to support mission design and to model and optimize spacecraft trajectories. It has been developed for many years. The tool is robust. It is maintained by NASA and a new version is released every year. This is the perfect tool to implement an interplanetary architecture. It is available and a great support can be found online as the tool is used by many different users.

HOwever, GMAT has two drawbacks. The first and main one is that is does not enable a complete assessment of the communication performance of the architecture. It is possible to implement a communication technology but the freedom on what can be done is limited. The communications for deep-space is restricted to the use of the DSN. It is not possible to implement another ground segment. The communication functions are limited to the analysis of "DSN range" and "Doppler data" [63]. To the best of the author knowledge, the current version does not provide link budgets. Generally people using GMAT for communication purpose design the architecture in GMAT, export the data and perform the link budget in another tool as explained by Culver et al. [64]. As a result, using GMAT implies the use of two different tools for the architecture and the technology. The capabilities required are not provided. Besides, GMAT is not very user-friendly. The interaction with GMAT implies the use of a graphical user interface (GUI) and a script language close to MATLAB.

Table 3.3: Comparison of the different modeling and simulation environments

	Capabilities	**Robustness**	**Availability**	**User-friendliness**
New tool	green	red	red	yellow
GMAT (by NASA)	red	green	green	red
STK (by AGI)	green	green	green	green

Systems Tool Kit (STK) by AGI

The last option considered is the software STK developed by AGI. STK is a four-dimensional modeling, simulation, and analysis environment for objects from land, sea, air, and space. It is developed by AGI and used by many companies in a broad spectrum of fields. The software is thus robust. AGI has a very responsive support via emails. The software is available.

The real assets of STK are its capabilities and its user-friendliness. It is possible to completely model, simulate, visualize and analyze an architecture of satellites and ground stations. The characteristics of existing satellites and ground stations are available in the database of the software. A lot of reports can be created about access, coverage, computation of distances, communication. The different existing communication technologies can be implemented, including optical communications. All the variables to design such a technology can be specified. A protocol can be specified too. Moreover, the software is very intuitive and easy to learn thanks to the numerous tutorials available online [65]. It produces good visualizations of the trajectories and the communication links. It is very user-friendly. The advantages and disadvantages of the different environments available are summarized in Table 3.3. Based on the criteria established at the beginning of the section, the best option for the present work is to use STK designed by AGI.

Once the architectures are implemented, they can be evaluated and finally ranked to determine the "best" alternative for the set of requirements selected. This calls the third research question: "How can communication architectures be consistently ranked?"

3.5 Evaluation and ranking

This section portrays the evaluation and the ranking of the architectures. It offers a hypothesis to answer the third research question. From the experiment 2, the framework is built. Then, the architectures are implemented and evaluated before being ranked.

3.5.1 Decision-making techniques

In the "Background" Chapter, different gaps were identified on the architecture comparisons. The two first gaps result from the assumptions on which the comparisons stand. Neither the requirements nor the presumed technology capabilities are consistent from one study to another. That leads to the impossibility to perform relevant comparisons. These two gaps were addressed in the previous sections. The last gap is related to the way architectures should be compared. The comparisons are incomplete because of the large number of existing concepts and the limited human brain capabilities. In addition, no specific technique is proposed to enable objective comparisons.

Decision-making is defined by the Merriam-Webster's dictionary as "the act of making up one's mind, judging or reaching a conclusion about something" [66]. Thus, decision-making is the process of sufficiently reducing the uncertainty about the alternatives to allow decision-makers to make reasonable and objective choices among them. In engineering, decision-making is almost always an arduous process as the purpose of a system is generally multiple, the number of requirements is important and requirements are often conflicting. Techniques called Multi-Criteria Decision-Making (MCDM) methods have been developed to tackle those challenges. These methods aim at supporting decision-makers in performing objective choices when numerous and conflicting evaluations are involved [67].

The number of MCDM techniques developed in the last decades is high and, as is often the case, there is not an overall best solution. The method selected is very much problem-dependent. As a result, it is important to discuss the characteristics required for the selected technique. They are presented in the following. First, the technique chosen has to be able to deal with the data available in the present problem. The alternatives that have to be ranked. The architectures are obtained from a literature review. Thus, although the design space is continuous, the set of alternatives compared is **discrete**. Besides, each alternative is evaluated with respect to each criterion in a **quantitative** way. In the present problem, the criteria are the requirements. The evaluation is quantitative.

Second, the outcome of the methodology has to be a **ranking**. The goal is not to draw some trade-offs or to perform pairwise comparisons but to assert which of the architectures is the best for a given set of requirements. The technique chosen needs to be able to support **weighting scenarios**.

Lastly, the number of alternatives is foreseen to be very large. Thus, the technique has to be able to support a **large number of alternatives**. The methodology designed here aimed at being extended. For the same reasons as for the requirement mapping, the technique has to be **transparent** and **structured**.

The characteristics to be satisfied by the selected method are now established. As above mentioned, the literature is rich in MCDM techniques. Many classifications and methods of selection of MCDM have also been proposed by various authors. In the following, one of the most accepted classification is reviewed in order to select the category from which the technique has to be chosen. Then, a further sorting of the remaining techniques is done following guidelines proposed by Zardari [68], and Guitouni and Martel [69]

First, many factors come into consideration after deciding which decision-making is the best suited for the problem at hand. These factors are presented below [70].

- The set of alternatives: Is it a discrete or a continuous problem?

- The measurement scale: Is the information qualitative, quantitative or mixed? What is the scale used?

- The valuation function: How is the score characterized? Is it a standardized score, a linear function, by value or by utility?

From these questions, Roy derived three categories of discrete methods [71].

1. The first category consists of **elementary methods**, also called simple methods or interactive local judgment approach methods. These methods alternate calculation steps and dialog steps relying on subject-matter expert judgments. They compare solutions using a pairwise comparisons (meaning comparing two elements at each step of the loop) or a ranking process (meaning an alternative ordering using verbal, alphabetical or numerical scales).

2. The second category consists of the **unique synthesis criterion approach methods**. They aggregate the different point-of-views into a unique function which will be later optimized. This category can be divided into two different sub-categories.

    - The **Multi-Attribute Utility Analysis methods** (MAUA) evaluate what is called "the attractiveness" of each alternative in terms of three discrete elements: impact of the alternatives relative to the decision criterion, the weight values of relative preference of each criterion and, if the effect score uses different scales, they must be normalized.
    - The **Qualitative methods** include the Analytical hierarchy process (AHP), the regime method, the permutation method and the Evamix method. The first two use pairwise comparisons whereas the last two use an effect's table.

3. The third and last category is the set of **outranking synthesis methods**. They are based on the development of an outranking relationship. It contains the decision maker's preferences and it is used to help the decision-maker towards a final choice.

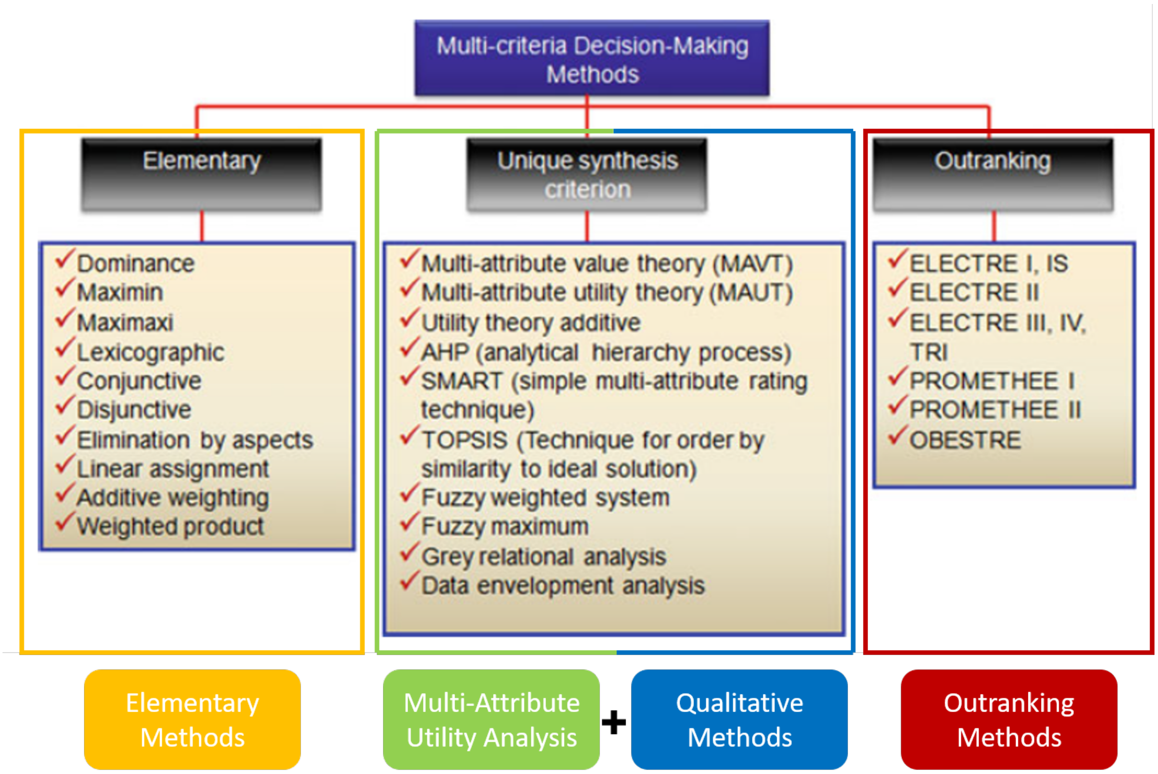


Figure 3.14: Classification of MCDM techniques

They regroup the various ELECTRE methods (ELimination Et Choix Traduisant la REalite, ELimination, or Choice Expressing Reality, in English), among others.

These three categories are represented on Figure 3.14.

First, the elementary methods are discarded because it will be impossible to do pairwise comparisons of thousands of architectures or to rank thousands of architectures on a specific scale in the presence of several requirements. These methods cannot support a high number of alternatives. The categories left are compared using additional characteristics: transparency, computation and cost, as illustrated in Table 3.4. This table does not list the methods themselves but sub-categories. As the number of alternatives is large, the costs have to be low and the computation simple. As a result, the sub-categories of weighted summation, ideal point method and evamix method are of interest.

Using the classification process proposed by Zardari [68] and presented on Figure 3.15, the evamix method can be withdrawn. The expected outcome is a ranking and the method

Table 3.4: Characteristics of MCDM techniques

Table 2.2 Characteristics of different multi-criteria methods

	Method	Information	Result	Transparency	Computation	Costs
Multi-Attribute Utility Analysis	Weighted Summation	Quantitative	Performance scores/ranking	High	Simple	Low
Multi-Attribute Utility Analysis	Ideal Point Method	Quantitative	Distance to target/ranking	Medium	Simple	Low
Multi-Attribute Utility Analysis	Evaluation by Graphics	Qualitative, Quantitative and Mixed	Visual presentation	High	Simple	Low
Outranking Methods	Outranking Methods	Quantitative	Ranking/ incomplete ranking	Low	Very complex	Medium
Qualitative Methods	Analytical Hierarchy Process (AHP)	Qualitative	Performance scores/ranking	Low	Complex	Medium
Qualitative Methods	Regime Method	Qualitative, Quantitative and Mixed	Ranking/ probability	Low	Very complex	Low
Qualitative Methods	Permutation Method	Qualitative	Ranking	Low	Very complex	Medium
Qualitative Methods	Evamix Method	Mixed	Ranking	Low	Simple	Low

deals with quantitative data.

The remaining sub-categories of interest are Multi-Attribute Utility theory, weighted summation and ideal points. This reasoning process leaves five corresponding techniques described by Guitouni and Martel as followed [69]:

- **TOPSIS (Technique for Order by Similarity to Ideal Solution**: "The chosen alternative should have the profile which is the nearest (distance) to the ideal solution and farthest from the negative-ideal solution."

- **MAVT (Multi-Attribute Value Theory)**: "Aggregation of the values obtained by assessing partial value functions on each criterion to establish a global value function V. Under some conditions, such V can be obtained in an additive, multiplicative or mixed manner."

- **UTA (Utility Theory Additive)**: "Estimate the value functions on each criterion using ordinal regression. The global value function is obtained in an additive manner."

- **SMART (Simple Multi-Attribute Rating Technique)**: "Simple way to implement

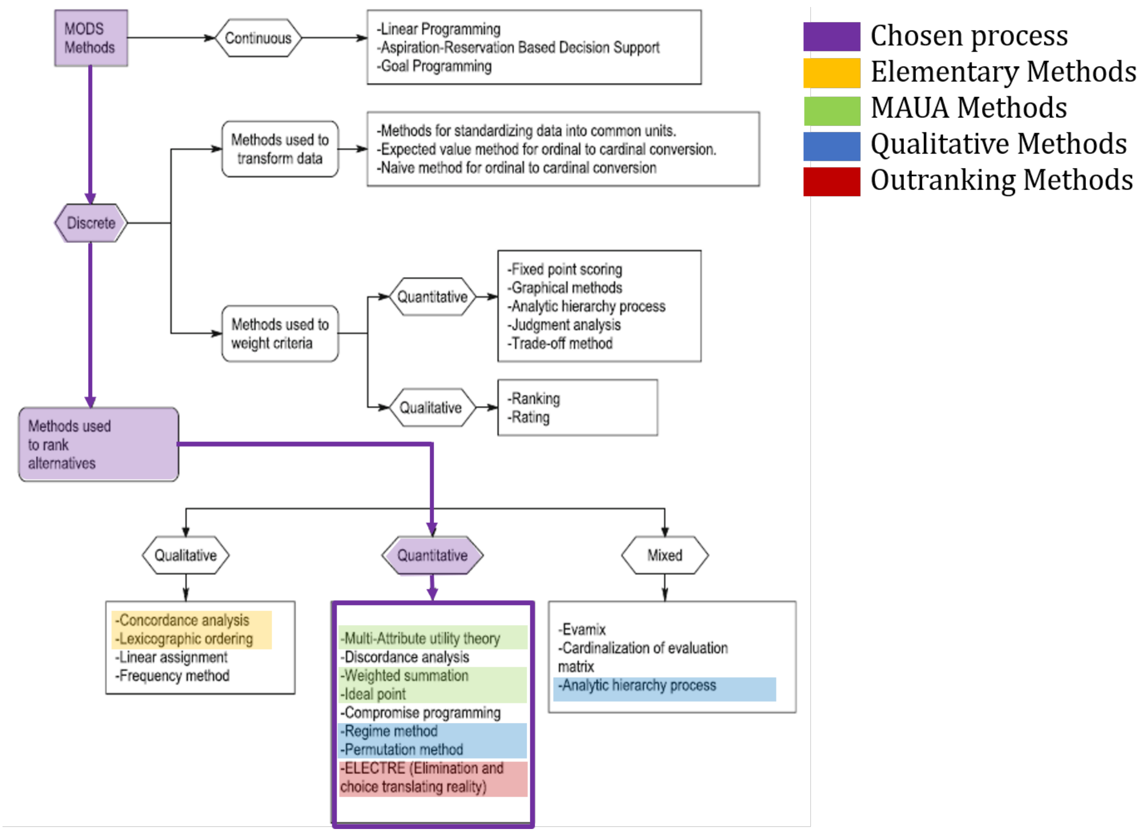


Figure 3.15: One of the possible method to select a MCDM [68]

the multi-attribute utility theory by using the weighted linear averages, which give an extremely close approximations to utility functions."

- **MAUA (Multi-Attribute Utility Theory)**: "Aggregation of the values obtained by assessing partial utility functions on each criterion to establish a global utility function U. Under some conditions, U can be obtained in an additive, multiplicative or distributional manner."

Guitouni and Martel draw some guidelines and assessed each method [69]. They depict some of the main characteristics of each technique and compare them. From, their analysis, the TOPSIS is the only method among the five remaining, to offer a direct rating elucidation mode. Thus, this is the technique selected.

3.5.2 Hypothesis

TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution (PIS) represented by A_+ on Figure 3.16 and the longest geometric distance from the negative ideal solution (NIS) represented by A_- on the same figure [72].

TOPSIS is used because of its simplicity and its ability to consider a non-limited number of alternatives and criteria in the decision-making process. It is also a systematic computational procedure that can support weighting scenarios. Finally, it is simple and structured and presents a ranking as an outcome.

The different steps of TOPSIS are as follows [73]:

1. Creating an evaluation matrix consisting of alternatives A_i and metrics R_j as illustrated on Figure 3.17.

2. Normalizing the matrix by dividing each number r_{ij} by $\sqrt{\sum_{k=1}^{m} {r_{kj}}^2}$.

3. Establishing the relative importance of each criteria (weighting scenario): to each metric R_j, the weight w_j is associated. The sum of w_j has to be equal to 1.

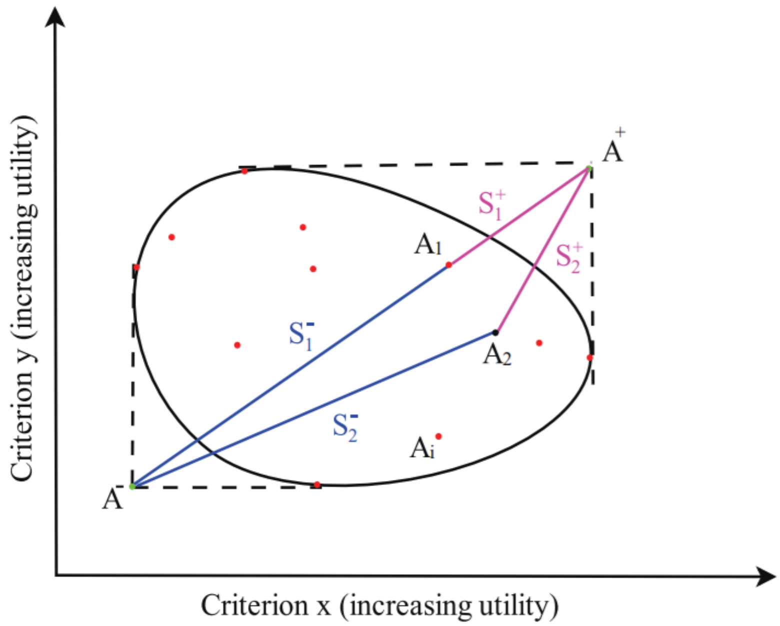


Figure 3.16: Illustration of the computation of the distance from the PIS and NIS in the TOPSIS technique

4. Applying the weight, multiplying each column by the associated w_j.

5. Identifying if a criterion is a "Benefit" or a "Cost". A benefit has to be maximized whereas a cost has to be minimized.

6. Identifying the positive ideal point and the negative ideal point. For each column, the positive ideal point is the maximum of the column if the criteria is a benefit, the minimum otherwise. The negative ideal solution is the minimum of the column if the criteria is a benefit, the maximum otherwise.

7. For each alternative, calculating the distance from the positive ideal point S_{i*} and the distance from the negative ideal point S_{i-}.

8. Ranking the alternatives using the relative closeness given by $C = \frac{S_{i-}}{S_{i-}+S_{i*}}$

To conclude, the hypothesis associated with Research Question 3 is the following.

$$DM = \begin{array}{c} \\ Alt_1 \\ \vdots \\ Alt_i \\ \vdots \\ Alt_m \end{array} \begin{array}{c} \begin{array}{ccccc} R_1 & \cdots & R_j & \cdots & R_n \end{array} \\ \begin{bmatrix} r_{11} & \cdots & r_{1j} & \cdots & r_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ r_{i1} & \cdots & r_{ij} & \cdots & r_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ r_{m1} & \cdots & r_{mj} & \cdots & r_{mn} \end{bmatrix} \end{array}$$

Figure 3.17: Evaluation matrix for the TOPSIS

HYPOTHESIS 3: *If* a Technique for Order Preference by Similarity to Ideal Solution is implemented *then* the comparisons performed on the communication architectures for different weighting scenarios are relevant.

In order to verify Hypothesis 3, Experiment 3 is performed. A set of requirements with the associated weighting scenario is selected. The list of alternatives is obtained from Experiment 2. The matrix linking the requirements to the alternatives is filled using the framework previously designed. Then, the TOPSIS is performed. The experiment is validated against the existing comparisons found in the literature and described in the "Background" Chapter. Because these comparisons present some inconsistencies, it is expected that some discrepancies could be found between their results and the results of this research. The verification criteria are as follows:

1. Are all the alternatives ranked?
2. Does the resulting ranking follow the trends expected from the literature?
3. Does the resulting ranking vary from one weighting scenario to another, in a cogent way?

3.6 Summary

Research questions and hypotheses have been derived to answer the objective of the thesis. A summary is provided by Figure 3.18.

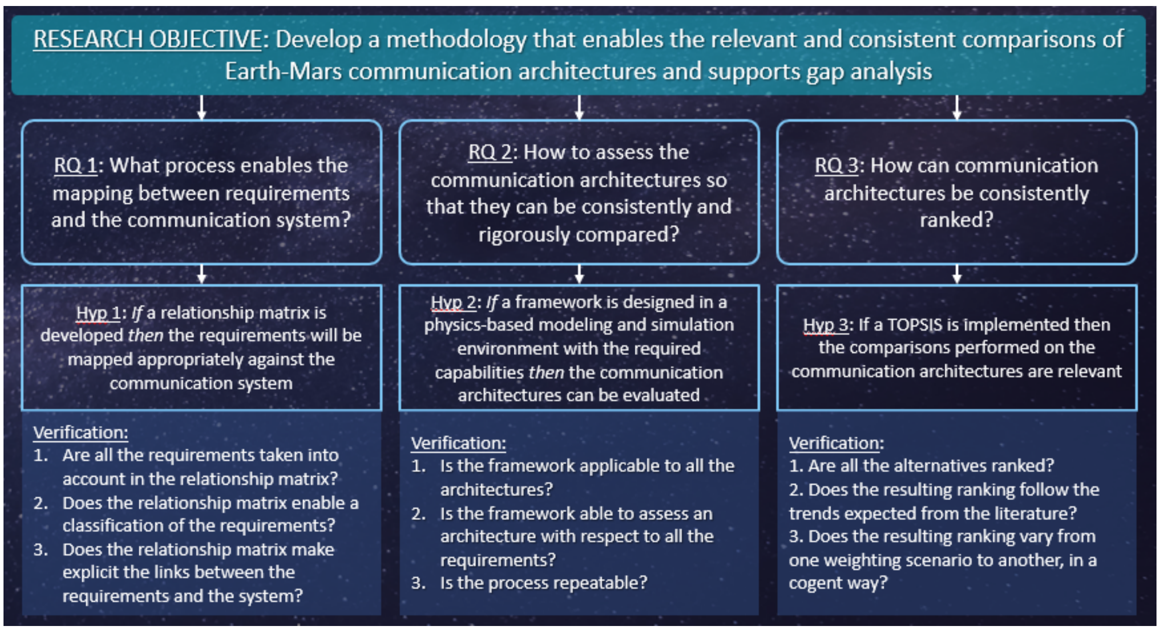


Figure 3.18: Summary of the problem

CHAPTER 4

METHODOLOGY FORMULATION

4.1 Methodology overview

The previous chapter detailed the definition of the problem and laid out the research questions and the related hypotheses. As discussed, the research focus of this thesis is to enable relevant comparisons of Earth-Mars communication architectures. To do so, a methodology needs to be developed, addressing the research questions formulated in the previous chapter. The steps that defined the proposed approach are depicted here. The methodology follows the typical top-down design decision support process illustrated on Figure 4.1. This process is composed of six steps.

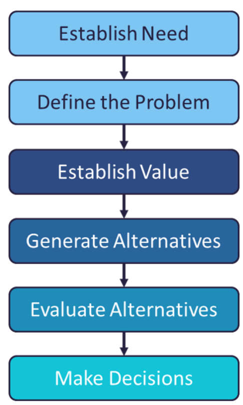


Figure 4.1: Generic top-down design decision support process

1. Establish the need: This part of the process has been described in the first two chapters of this document, the "Motivation" and the "Background" Chapters, highlighting the need for designing a permanent communication architecture between the Earth and Mars and addressing the existing gap in the architectures comparisons.

2. Define the problem: This step has been characterized in the "Problem Definition" Chapter, identifying the research questions and the associated hypotheses.

3. Establish the value: This step corresponds to the definition and the mapping of the requirements against the technology capabilities (RQ 1).

4. Generate alternatives: This step is the collection of the architectures through the survey and the implementation of these architectures in the framework designed in STK (RQ 2).

5. Evaluate alternatives: This step coincides with the evaluation and the ranking of the alternatives through the different TOPSIS (RQ 3).

6. Make decisions: This step concludes the process by performing a gap analysis and sensitivity analysis.

The first two parts of the process have already been described. The following three parts are explored in depth in this chapter. The last step will not be discussed in the thesis. It appears as future work in the "Conclusion" Chapter.

4.2 Step 1: Mapping the requirements

The objective of the first step is to establish and define a set of the requirements for our study, emphasize the links between the requirements and the communication system and map the links between the two. In this step, experiment 1 is carried out as a mean to test the hypothesis 1. This step is divided into three parts.

1. Defining the requirements.

2. Establishing the taxonomy described in the problem definition.

3. Implementing the relationship matrix.

A set of requirements has to be define for our study. From the methodological gaps established in the "Background" Chapter, we know that there is a lack of definition in the requirements for the design of Earth-Mars communication architectures. A review of the requirements for the existing concepts of communication architectures is performed to establish a set of requirements that correspond to our problem. From this review, our requirements are defined and the ranges for each requirement are fixed.

The second part of this step aims at characterizing the links and the impacts of the requirements on the communication system. The requirements are classified according to the taxonomy established in the "Problem Definition" Chapter: those impacting the communication technology on one side, those impacting the architecture on the other side.

Once the taxonomy performed and the linking between the requirements and the communication system established, the relationship matrix is implemented. This relationship matrix is used at step 2 to define the metrics against which the architectures will be evaluated. At the end of the step, a validation of the evaluation criteria is carried out. In particular, we verified that all the requirements are taken into account in the relationship matrix, that the relationship matrix enables the classification of the requirements and that all the links spotted between the requirements and the system are translated in the relationship matrix. If the relationship matrix is wrong, all the following results will be wrong too.

4.3 Step 2: Building the framework

The second step corresponds to the generation of the alternatives in the generic top-down design decision support process. In the particular methodology described here, the generation of the alternatives encompasses finding the alternatives from the literature and implementing them in a modeling and simulation environment that enables a reproducible evaluation of the architectures, based on the same assumptions. The alternatives are not generated but taken from the literature review. The experiment 2 is carried out a mean to test the hypothesis 2. This step is divided into five parts.

1. Designing the framework in STK.

2. Defining the metrics.

3. Validating the framework via two test cases.

4. Performing a survey of all the existing concepts of communication architectures between the Earth and Mars.

5. Implementing the architectures in STK

The experiment 2 is the design of a framework enabling the evaluation of the architectures based on the same assumptions and in a repeatable way. The framework is designed in STK. The environment and the way to implement the architectures are described.

The framework is later used to evaluate the architectures. Thus, a metric has to be associate to each requirement. The metrics as defined as well as the way to obtain a value for each metric for each architecture.

Then, the framework has to be validated to be sure that the results obtained for each metrics are relevant and that there is no mistake in the implementation. The validation is executed through two test cases. The two test cases are two existing concepts for which the results for the metrics are known. These test cases validate the framework and the way to implement the architectures.

Next, alternatives have to be generated. The goal of this study is not to explore the entire continuous design space but to find the best existing concept for a given set of requirements. Thus, existing architectures have to be identified and characterized. This long-term task has been initiated in the "Background" Chapter. It has to be completed. A survey of architectures results from this step.

Last but not least, everything is put together. The architectures are implemented in the framework. The implementation concludes the step 2.

4.4 Step 3: Ranking the architectures

The purpose of Step 3 is to rank the architectures for different weighing scenarios applied to the requirements defined at step 1. The ranking is performed through a TOPSIS. The experiment 3 is carried out a mean to test the hypothesis 3. This step is divided into four parts.

1. Completing the evaluation table.
2. Establishing different weighting scenarios corresponding to interesting trades.
3. Performing the TOPSIS for the different weighting scenarios.
4. Discussing the results and comparing the different scenarios.

The first part of this step is to evaluate the architectures using the framework previoulsy defined. The goal is to fill the evaluation matrix mapping the architectures against the metrics. An example of evaluation matrix is presented on Figure 4.2. This matrix will be used to complete the TOPSIS.

$$DM = \begin{array}{c} \\ Alt_1 \\ \vdots \\ Alt_i \\ \vdots \\ Alt_m \end{array} \begin{array}{c} \begin{array}{ccccc} R_1 & \cdots & R_j & \cdots & R_n \end{array} \\ \begin{bmatrix} r_{11} & \cdots & r_{1j} & \cdots & r_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ r_{i1} & \cdots & r_{ij} & \cdots & r_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ r_{m1} & \cdots & r_{mj} & \cdots & r_{mn} \end{bmatrix} \end{array}$$

Figure 4.2: Evaluation matrix for the TOPSIS

A few different weighting scenarios have to be established to illustrate different interesting trades and to verify that the results change with different requirements in a cogent way. The weighting scenarios include a scenario giving the same weight for all the requirements. For each weighting scenario, the TOPSIS is performed from the evaluation matrix. Additional scenarios could be created but the goal of this thesis is to demonstrate a methodology and not to do an extensive discussion on the ranking of communication architectures.

This step ends with the discussion of the results for each scenario. Some trends are underlined. The results for the different scenario are compared too. The objective is to see if there are some architectures that perform well for all the scenarios and some that are bad for all the scenarios. Some conclusions emerge from these results.

CHAPTER 5
STEP 1 - MAPPING THE REQUIREMENTS

This Chapter aims at defining the requirements for the present study and map them against the communication system. As described in the Chapter "Methodology Formulation", section 4.2, the first step of this thesis includes a literature review of requirements for an Earth-Mars communication architecture, the definition of our requirements and the mapping of these requirements to the communication technology and to the architecture.

5.1 Definition of the requirements in past studies

Before evaluating the architectures, a set of requirements with a threshold to reach for each requirement has to be established. The research goal of this thesis is to enable a reliable and continuous communication link between the Earth and Mars for manned missions through the design of a permanent architecture. This goal is not a properly defined requirement, it has to be translated into quantifiable engineering values. To do so, we investigated the literature to seek for the commonly admitted requirements for such a goal. For the Earth-Mars communication architectures detailed in the survey performed in the next chapter, the requirements driving the design of each architecture are identified. Appendix presents a table with the architecture, the type of architecture and the requirements associated with it. The main conclusions from this table are described in the following figure 5.1.

As underlined in the "Background" chapter, there is a gap in the definition of the requirements. Most of the time, they are not properly defined. Often, papers only state a general purpose of the architecture such as: the architecture has to provide a "complete and continuous coverage". In the Appendix, in the Requirements column, the exact sentence used in the articles were copied into quotation marks. Below, this sentence is translated into proper quantifiable requirements. This translation is the result of an interpretation of their assumptions. For example, a "complete coverage" is translated by "surface covered: 100%". A "continuous link" is translated by "link availability: 100%". Besides, the value that has to be reached by the requirements is not set most of the time. For example, the requirement is stated as "high bandwidth" or "coverage of the area of interest" without specifying the area of interest.

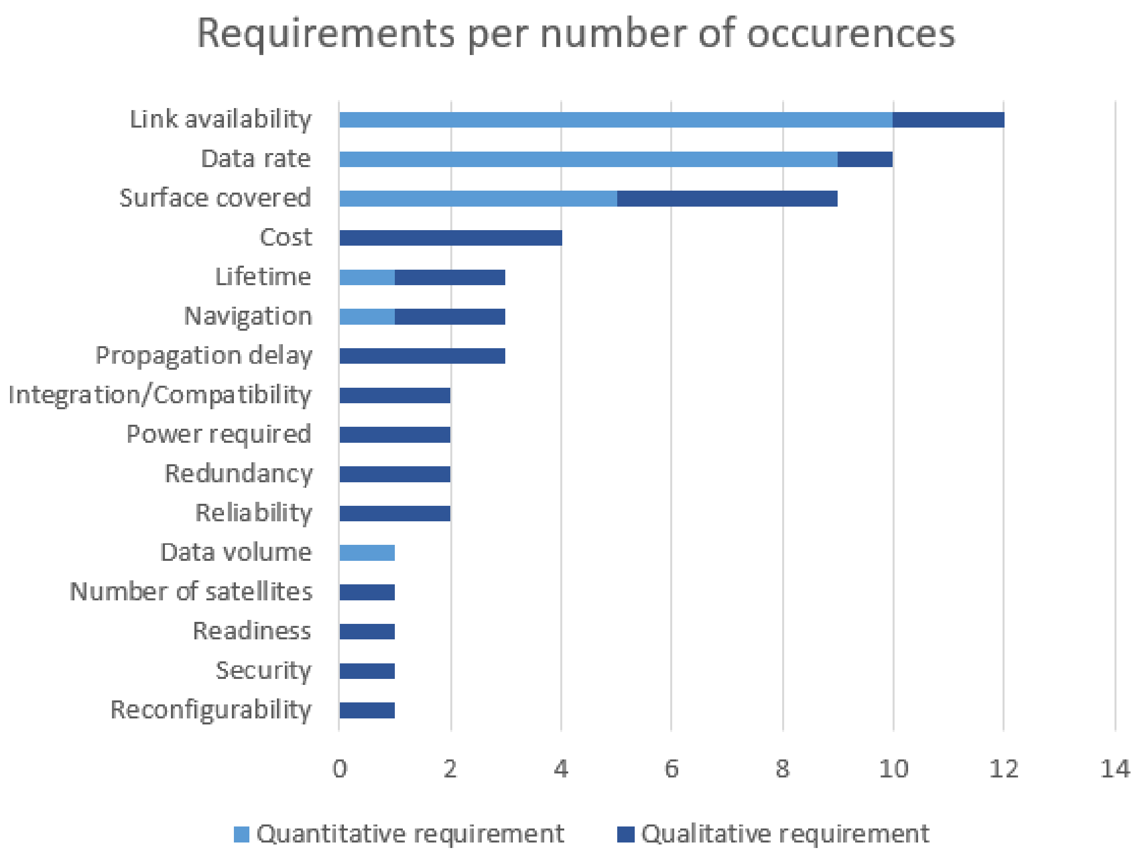


Figure 5.1: Classification of requirements by the number of occurrence

From the appendix table, the requirements are extracted, and the results are presented on Figure 5.1. If several architectures correspond to the same set of requirements, the requirements are counted only once (architectures **AD**, **AE**, **AF**, **AG**, architectures **AN**, **AO**, **DD**, architectures **EB**, **EC**, **EF**, **EG**, **EH**). Thus, the total number of sets of requirements is twenty. Among those twenty sets, the three most common requirements are the link availability, the data rate and the surface covered. Most of the time, the link availability and the data rate have a value that has to be reached. The distributions of the values for the two requirements are presented on Figure 5.2. Regarding the link availability, the value ranges from 95 percent to 100 percent. In two thirds of the cases, this requirement is set to 100 percent. Concerning the data rate, the value is widely spread ranging from 100 kbps to 8 Gbps. However, there is a concentration on the value 10 Mbps. In some studies, the authors specify a different value for the uplink and the downlink or a different value for the long ranges and the short ranges. For the coverage, a value is specified in only half of the papers. When it is specified, it is a complete coverage that is required.

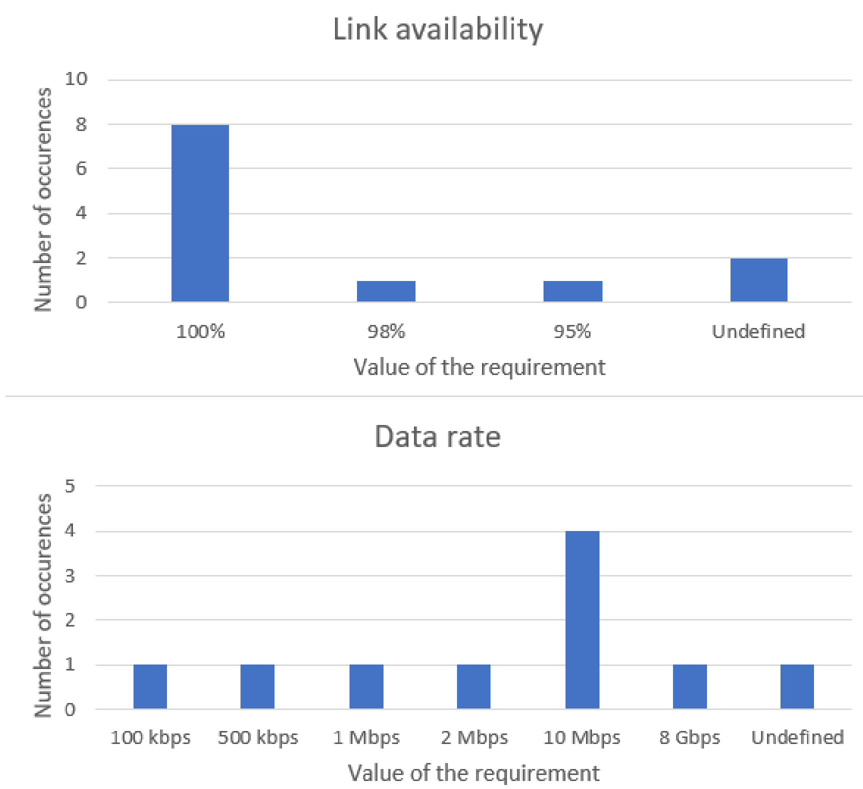


Figure 5.2: Value for the link availability requirement and the data rate requirement

After link availability, data rate and surface coverage comes a series of requirements cited two to four times. A value to reach is rarely set for those requirements. Among them, some act more like a constraint to the system, meaning that those values have to be minimized. This is the case for the cost, the propagation delay and the power required. The navigation is a sometimes stated as a service that has to be provided by the architecture in addition to communications. In one case, the navigation precision required is specified.

In this series, the first non-functional requirements appear such as the compatibility, the redundancy and the reliability. A non-functional requirement is defined by Cysneiros et al. as the following: "[Non-functional requirement], as opposed to functional ones, do not express any functionality to be implemented in the future information system. On the contrary, they express behavior conditions and constraints that must prevail" [74]. Non-functional requirements are harder to quantitatively evaluate. At the end of the list, cited only once, the data volume, the number of satellites, the readiness, the security and the re-configurability appear. In one case that is not presented here, the design of the architecture is driven by the choice of the technology. The latter uses faster-than-light communications.

5.2 Review of the requirements for an Earth-Mars communication architecture

5.2.1 Presentation

When looking at the architectures, the requirements are often poorly defined and subject to our interpretation. This is why a specific review of the requirements for a telecommunication system between the Earth and Mars is performed, to see if a clearer and better definition of those requirements exists. The full literature review is presented in the Tables in Appendix B. The Tables gather a list of interesting papers targeting the requirements for the communication system which is being designed here. For each paper, it introduces the general idea of the paper. Then, it details some of the following:

- the global goal of the system designed,
- the services required by the system,
- the needs,
- the requirements,
- the metrics associated with the requirements to evaluate the system.

The reader has to keep in mind that the idea of the requirements' study made here is not said to be exhaustive in the analysis of the papers studying the requirements for communication systems. First, the study is centered on communications between the Earth and Mars for manned missions. When this is not the main purpose of the study, the study can be excluded. Then, a lot of papers retake the same studies and formulate it from another point of view. In particular, the NASA's vision has been studied many times. In that case, the latest version or the most explicit are considered, letting apart other papers. Finally, some studies of requirements are very specific to a certain mission. In that case, either the study is cited in the survey of the architectures and the requirements appear in the section above, or it is excluded. The interesting elements of the review performed are presented in the following.

5.2.2 The review

The first paper is an old paper written by White for NASA in 1986 [75]. It is the first analysis of the requirements on a communication system for manned missions to Mars. First it defines the design drivers of a communication system that are the mission objectives, the mission duration and the number of vehicles. In the present case, we have to overcome these drivers as they are mission-specific whereas our goal is to create an architecture that can be used for every robotic and manned mission to Mars. This is the first challenge of our design. In the rest of the article, White details the key communication elements that have to defined. They are:

- the presence or not of a relay satellite,
- the frequency,
- the coverage,
- the data rate and

- the communication security.

These key elements are still relevant thirty years later. This article sets the basis of the discussion.

Since 1986, the technologies and the vision of NASA have evolved. Now, other major space agencies have their own concepts. The next two papers introduce the visions of ESA and NASA respectively. The concept of Interplanetary Internet elaborated in the "Background" Chapter is the concept of ESA. Sanctis et al. develop the concept [41] starting with the setting of the three services that has to be provided: the time insensitive transfer of large data, the time sensitive live video streaming for the control of rovers and the telemetry, tracking and commands (TT&C) of landing elements and orbiters. From those services, they derive the top-level application needs that include the type of application (video, images etc), the number and location of data users, the number and locations of data sources etc. Then, they describe the elements that could be part of the communication architecture, but they do not go into details. On the other hand, Bhasin and Hayden introduce the NASA vision of an interplanetary communication network spreading far beyond Mars [76]. The goal is to provide an "advanced, integrated, communications infrastructure [that] will enable the reliable, multipoint, high data rate capabilities needed on demand to provide continuous, maximum coverage of areas of concentrated activities, such as in the vicinity of in-space outposts, the Moon or Mars". This network is designed based on the needs expressed by the NASA Enterprises in 2010. As in the previous article, the required services are: Bidirectional voice, HDTV, Data, TT&C, Science files, Remote control, Emergency links and backbones data services. From the required services, a list of requirements for a deep-space communication architecture is derived. This list is the most exhaustive study found in the literature and is given in Table 5.1. From that, a concept is elaborated but the location and the number of elements that form the architecture are not completely defined. These two visions of ESA and NASA define concept of an interplanetary communication network but they do not go down to the full specification of an architecture.

Table 5.1: Requirements for a deep-space communication architecture by NASA [76]

Table 2: Required characteristics of the infrastructure.

Required Characteristic	Rationale
Be available 24/7.	Basic requirement of human missions and most missions requiring low latency data return.
Integrated Architectures	Use of standard interfaces (hardware, wireless, and protocols) across the infrastructure increases data routing options and reduces costs of implementation.
Low cost, modular and efficient.	This can be achieved by adapting commercial technology standards to use in space.
Handle multipoint connections to multiple nodes simultaneously.	Essential for broadcasting data to many spacecraft simultaneously; for inter-spacecraft coordination of timing, maneuvers, and collaborative science data gathering; and for enabling autonomous end-to-end routing of data.
Highly reliable connections	Connections must be reliable to meet the very high data rates or the required characteristics will not be met.
Long life expectancy.	High cost of development and space flight dictates lifetimes of greater than 20 years.
Highly reconfigurable	To accommodate upgrades and enable growth in capabilities over time.
Be secure.	Cannot allow intruders to take control of the systems nor allow sampling of private data.
Connect End-to-end	Enabling data to move on demand from user to spacecraft instrument or back greatly reduces operations support costs.
Handle multiple robotic and human missions simultaneously.	Essential for providing communication routes for many spacecraft simultaneously so that many data streams can be routed from end-to-end autonomously.
Multiple quality of service levels	QoS diversity is required to handle voice, video, science data and control data simultaneously.
Minimum latency within the networks.	Required for maintaining the tightest possible control loops that are necessary in most human-operated remote missions. It also helps for keeping human-human communications as close to real-time as possible.
Provide navigation capabilities within telemetry signals.	Needed for missions that must coordinate their activities and for flying in formations.
Operate in extreme environments	In-space hardware must survive solar flares and cold temperatures. Planetary/moon hardware faces large temperature swings (Moon, Mars), high radiation (Europa), high temperature (Mercury).

Edwards is the first author of two articles that drwas from the NASA vision and bring out a tangible concept from it [43, 77]. His goal is to design a communication relay to overcome deep-space communication challenges. The challenges are the ones that have already been described before and include, among others, the return of large data volumes, highly constrained mass, volume and power for all the elements, high-risk mission events such as entry, descent, and landing (EDL) for which the telemetry is critical. In the article *Relay communications strategies for Mars exploration through 2020*, he establishes the key communication figures of merit before summarizing the current NASA's strategy in terms of communication. This article acts like the updated version of White's article. The key figures of merit he extracted are:

- the data return (high bandwidth required to transmit high definition videos),
- the mass and energy constraints,

- the contact opportunities and
- the critical events (like EDL).

Then, he reviews the current Mars orbiters and the benefits of a communication relay. The limitation of this article is that only science missions are considered and no manned missions. The paper *Strategies for telecommunications and navigation in support of Mars exploration* goes further in the design and evaluation of relay options. In this paper, the needs are explained by classes of missions. In the case of a manned mission, the needs are the following:

- near continuous communication with Earth,
- high data return (high data rate, high bandwidth data link, high data volume),
- TT&C, including special support during critical events such as EDL or launch,
- mass and power available,
- reliability,
- point-to-point communications,
- GPS-like navigation system.

This list of needs can be easily connected to the list of corresponding requirements established in the previous section and visualized on Figure 5.1. Then, Edwards derives some metrics against which he evaluates different relay alternatives. Again, like in the previous section, Edwards does not give any value to be reached for each requirement, for example the percentage of availability or the data rate required.

The process of defining the needs, deriving the requirements and then some metrics to evaluate the architectures is the process we are following in this thesis. Edwards follows the process on the relays. The two next studies carried out by Bell [42] and Talbot-Stern

Table 5.2: Requirements and metrics by Bell [42] and Talbot-Stern [46]

Bell	Talbot-Stern
Performance goals: - Provide global coverage - Provide high capacity, low latency communication support to the equatorial regions - Maximize coverage - Minimize the variations across the surface in terms of coverage and performance - Redundancy - Minimize orbital maintenance	Requirements: 1. The communication system must provide several communication links for voice, data and video at minimum specified data rates. (100Mbps in short range and 1Mbps at least in long range) 2. The navigation system must provide sufficient surface coverage for accurate navigation and precision position location methods 3. The sensing system must provide real-time weather data, as well as other scientific results of the surface when required 4. The architecture should provide sufficient redundancy and robustness so no satellite failure will result in a mission abort or catastrophic mission loss (satellite life = 10 years including transit).
Metrics: - Passes/sol - Maximum Gap Time (MGT) between contacts - Mbit/Sol/Watt - Mean Response Time (MRT) - Mbit/joule	Metrics: - IMHEO (Injected Mass into High Earth Orbit): give an idea of the total mass requirement - Bit rate performance: total simultaneous system bit rate divided by the IMHEO

[46] use the process on constellations of satellites around Mars. The requirements and the associated metrics used to assess the architecture are presented in Table 5.2. The difference between the two studies is that Bell conclude that 4retro111 is the best constellation whereas Talbot-Stern does not conclude. As already underlined in the "Background" Chapter, the limit of these studies is that they only compare the constellation options and they do not perform any optimization of these constellations.

The last paper briefly described was written by Bergmann et al. [78]. It offers an exhaustive general description of communication requirements divided into two categories: the user requirements and the system requirements. These requirements are depicted on Figure 5.3. The second category derives from the first one. Deriving the requirements from the user to the system is the idea followed at the step 1. It is the only paper to offer some kind of classification for the requirements. However, it does not propose a mapping between the user requirements and the system requirements which is being done here.

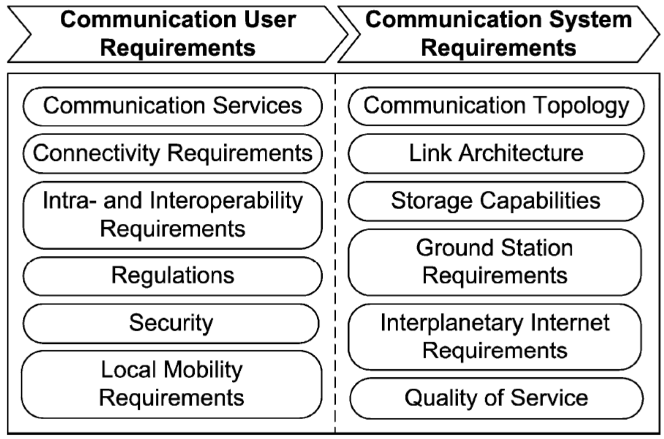


Figure 5.3: Classification of requirements by Bergmann et al. [78]

5.2.3 Summary

Several conclusions can be drawn from this review and will help us in the remaining work. Our research objective is to create a methodology to compare Earth-Mars communication architectures. First, this review gives an idea on how to build this methodology. It starts with an identified need: enabling a reliable and continuous communication link between the Earth and Mars for manned missions through the design of a permanent communication architecture. From this need, the requirements are derived. Some metrics have to be defined to evaluate the architectures. Finally, the architectures are ranked. This complete methodology is rarely achieved from the beginning to the end. Most of articles focus only either on the requirements, or on the design of the architecture. When the complete methodology is followed, the comparisons are incomplete. The work carried out here is thus new.

Second, this review acts like a guide for our methodology as every step has already been studied in one way or another. The transition from a primary goal to some requirements is the work done by Sanctis and Bhasin. The mapping of the requirements against the communication system (Step 1 of the present work) is similar to what Bergsmann et al. did, even if they did not go until the end of the mapping. The definition of the metrics deriving from the requirements (Step 2 of the present work) has been performed by Edwards, Bell and Talbot-Stern. Besides, this review gives a list of properly defined requirements. Our requirements can be picked from this list. It also gives some examples of metrics such as the passes/sol to evaluate the link availability or the data rate or data return to evaluate the communication performance.

Finally, an important lesson from this review is that even in a deep study of the requirements such as the one by Bhasin and Hayden, there is no range or common value to be reached for the requirements such as the link availability or the surface covered.

5.3 Requirements mapping

From the previous section, a list of common requirements corresponding to the type of architecture of interest has been made. From that list, the requirements for our study are selected. They are defined and classified according to their impacts on the communication technology and/or the communication architecture. The relationship matrix is filled.

5.3.1 Definition

As a reminder, the objective of this thesis is to demonstrate a methodology. For this reason, the case presented is kept as simple as possible for the sake of clarity and transparency. The essence of the problem is captured to make the methodology as understandable as possible. This is why the number of requirements is very limited and the choice of the requirements is oriented towards the requirements which are the simplest to evaluate architectures against each other. The choice of staying at a high-level of abstraction is made on purpose.

The goal of the system is to provide a reliable and continuous Earth-Mars communication link for manned mission. The main challenges identified for Interplanetary Internet are: the large propagation delay, the discontinuity of the link, the large path losses and the limited quantity of energy available. From the study of the requirements, it has been found out that the most cited requirements are the link availability, the data rate and the surface covered. These three requirements are relevant for our study and correspond to our goal. The link availability corresponds to the "continuity" of the communication link. The data rate is a good measure of the quality of the service provided in terms of communications. The surface covered corresponds to the desire of providing an architecture that support every Mars mission. Then, because we target manned missions, the propagation delay is a very important criteria emphasized by Edwards [77]. This requirement completes the list. Thus, the resulting top-level requirements tackled in the thesis are:

- Link availability
- Coverage
- Propagation delay
- Data rate
- Number of elements

The number of elements has been added to take into account the complexity of the architecture. The intent is to avoid having a solution with a multitude of small satellites close to each other that will do great in terms of communication performance but will be unfeasible due to a high cost and an important required deployment effort. Other requirements could be added such as the cost. Cost is one of the major driving elements in every space mission. It is discussed in "Future work".

Additional considerations could be added on non-functional requirements such as:

- reliability which is more likely to be translated in term of redundancy at a highest level on the architecture, multiple links would also provide resiliency and redundancy (fault tolerance),
- integration, compatibility or standardization which mostly affects the type of satellites and the protocols selected,
- level of development of the technology (TRL),
- complexity and maintenance,

- lifetime that derives from the two previous criteria.

However, non-functional requirements are harder to evaluate. This is why they are excluded from this study.

5.3.2 Mapping

Once the requirements are defined, they are reviewed one by one to assess the impact on the communication system.

Link availability

The first requirement is the link availability. This item has already been extensively discussed in the "Motivation" chapter while talking about the solar conjunction events. Indeed, the main reason of a link interruption are the obstruction by a planet, including the sun, and the alteration of the signal by charged particles in the deep-space. In the case of an obstruction by a planet, the link availability is correlated to the location of the satellites. The location of the satellites is a characteristic of the architecture. In the case of the alteration of the signal by charged particles, the link availability relies on the technology, as explained previously. As a result, the link availability is linked to both the technology and the architecture.

Coverage

Computing the surface of a planet covered by a satellite is a geometrical problem. This problem is illustrated on Figure 5.4. The accessible surface area, ie. the surface that can geometrically be covered by the satellite $A_{accessible}$, is a function of the altitude and the inclination of the satellite. Thus, it is a function of the location of the elements. Indeed, the accessible surface area is given by the Equation 5.1 with $d = R_M(1 \sin\theta)$ [79].

$$A_{accessible} = \pi({R_M}^2 - d^2) + 2\pi R_M \times d \quad (5.1)$$

The angle θ is related to the altitude of the satellite through the Equation 5.2. Consequently, the altitude of the satellite and the accessible surface area are connected.

$$\sin\theta = \frac{R_M}{R_{sat}} \tag{5.2}$$

On Figure 5.4, the angle θ corresponds to the angle of maximum coverage. In reality, the

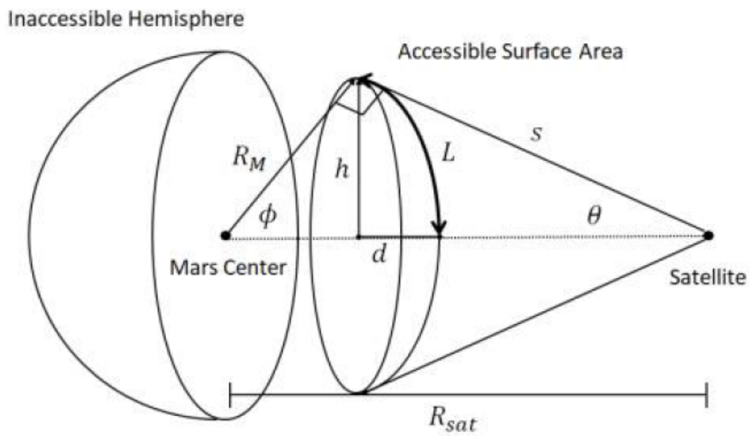


Figure 5.4: Geometry for the surface coverage [79]

angle to compute the actual accessible surface θ_{techno} is limited by the technology. The area covered is still given by Equation 5.1 but the R_M has to be replaced by R_{techno} defined by Equation 5.3.

$$R_{techno} = \sin\theta \times R_{sat} \tag{5.3}$$

The actual accessible surface is a function of the altitude of the satellite and the beam's angle of the communication technology. Consequently, the coverage is linked to the architecture and to the technology.

Propagation delay

As already detailed in the "Background" Chapter, because we consider only electromagnetic waves as a technology for this study, the propagation delay is directly linked to the distance between the elements through Equation 5.4

$$t = \frac{d_{tot}}{c} \tag{5.4}$$

c is the speed of the light in free-space. Its value is fixed to approximately 300,000 km/s. d_{tot} is the end-to-end distance travelled by the signal from the initial transmitter to the final receiver. The propagation delay is independent of the technology in the scope of the study but dependent to the location of the satellites, so dependent to the architecture.

Data rate

The fourth requirement is the data rate. Its expression depends on the communication technology chosen. For the optical communication, there is a theoretical relationship between the power transmitted by the antenna P_T and the data rate D_{rate}. This relationship is given by Equation 5.5 with R the range between the transmitter and the receiver, λ the wavelength, D_T and D_R the diameters of the transmitter aperture and the receiver antenna respectively, $(h\nu)$ the energy per photon, S the signal counts per decision interval (photo-electrons per bit), α the alpha level (bits per pulse), Q the quantum efficiency, F the signal losses in transmitter and receiver [80].

$$P_T = \left(\frac{4\pi R\lambda}{(\pi D_T)(\pi D_R)}\right)^2 \times (h\nu)\left(\frac{D_{rate}(S)}{\alpha Q F}\right) \tag{5.5}$$

A similar relationship exists for the radio-frequencies. The relationship translate a link between the power transmitted and the geometry of the communication hardware on one hand, the distance between the elements and the data rate. Thus, the data rate is linked to both the technology and the architecture. Regarding the technology, it is linked to its performance in terms of energy and the geometry of the hardware. Regarding to the architecture, it is linked to the location of the elements.

Relationship matrix

The number of elements is not discussed independently because it is a function of itself. It is a characteristic of the architecture and impacts the architecture only. From the description of the impacts of each requirement, it has been found that when a requirement impact the technology, it is related either to the pointing performance of the technology, to the sensibility to solar particles (what is called alteration in the matrix) or to the overall performance that is to say in terms of mass, size or power requirement. When a requirement impacts the architecture, it is related to either the number of elements, the location of the elements, or both. These relations are summarized in the relationship matrix Table 5.3. The "1" means that there is a connection between the requirement and the communication system. The "0" means that there is no correlation.

Table 5.3: Requirements mapping through a relationship matrix

	Technology			Architecture	
	Pointing	**Alteration**	**Performance & geometry**	**Number of elements**	**Location of elements**
Coverage	1	0	0	1	1
Link availability	1	1	0	0	1
Propagation delay	0	0	0	0	1
Data rate	0	0	1	0	1
Number of elements	0	0	0	1	0

5.4 Validation

HYPOTHESIS 1: *If* a relationship matrix is developed *then* the requirements are mapped appropriately against the communication system.

For this hypothesis, the validation criteria were the following:

1. Are all the requirements taken into account in the relationship matrix?

2. Does the relationship matrix enable a classification of the requirements according to their impacts on the communication system?

3. Does the relationship matrix make explicit the links between the requirements and the system?

In our study, five requirements are defined. Those five requirements are included in the relationship matrix and none of them has a row full of zero. This means that the relationship matrix take into account all the requirements and enable the connection between the requirements and the communication system. The first criterion is satisfied.

From the relationship matrix, it is known that the coverage, the link availability and the data rate impact the communication technology. On the other hand, the coverage, the link availability, the propagation delay, the data rate and the number of elements impact the communication architecture. From the relationship matrix, we have been able to divide the requirements among those that impact the technology and those that impact the architecture. The second criterion is satisfied.

From the relationship matrix, it is explicit what requirement impact which part of the system. Is does not only show if it impacts the technology or the architecture but also what aspect of the technology (pointing, alteration, performance and geometry) and/or of the architecture (location, number of elements). The third criteria is satisfied.

The hypothesis 1 is validated. The requirements are defined and mapped against the communication system. Now, they can be exploited to assess and rank the architectures.

CHAPTER 6

STEP 2 - BUILDING THE FRAMEWORK

This Chapter describes the design of the framework to evaluate architectures. As discussed in the Chapter "Methodology Formulation", section 4.3, this step encompasses the design of the framework, the description of the metrics to assess the architectures and the validation of this framework. It ends with a survey of the architectures proposed by different authors for Earth-Mars communications and an overview of the implemented architectures.

6.1 Building the framework

To efficiently compare those existing Earth-Mars communication architectures, the latter have to be evaluated exactly the same manner. This is why a repeatable framework for the evaluation is needed. The framework is built in the software STK (Systems Took Kit) developed by AGI and detailed in the following.

6.1.1 The environment

Before implementing the architecture itself, the environment has to be set. This environment is the same for all the architectures. The first elements to be introduced are the Sun and the two planets of interest, the Earth and Mars. The parameters for these planets are the ones defined by STK and depicted in Table 6.1. The ephemeris source selected to propagate the orbits of the Earth and Mars are "DE430". It is a JPL file that contains the ephemeris for the primary planets, Pluto, the Moon and the Sun from 1960 to 2060. As our architectures are simulated around 2023, this file is appropriate [65].

The second element to be added to our framework is the ground segment. As we focus on radiofrequencies, we arbitrarily select the NASA DSN as a ground segment. We could have chosen the ESTRACK, and that choice would have had any impact on the results

Table 6.1: Parameters in STK

	Sun	Earth	Mars
Radius (km)	695508.0	6378.137	3396.190
Gravitational parameter km^3/s^2	1.32712e+11	398600	42828.4

Table 6.2: Properties of the DSN antennas selected

Name	**DSS-25**	**DSS-34**	**DSS-65**
Location	Goldstone	Canberra	Madrid
Type	Parabolic reflector	Parabolic reflector	Parabolic reflector
Diameter	34-meter BWG	34-meter BWG	34-meter HEF
Uplink	X, Ka	S, X	X
Downlink	X, Ka	S, X, Ka	S, X

of the evaluation. As we only focus on assessing the communication, we do not take into account parameters such as the cost of using the DSN or the availability of the antennas. We assume that the antennas are available 24/7. Thus, we only need three antennas, one at each location of the DSN. The DSN has twelve antennas in activity as today November 12, 2018 [81]. As a reminder, the three locations are Goldstone in California in the United States, Tidbinbilla next to Canberra in Australia and Robledo near Madrid in Spain. The selected antennas receive and transmit in X-band, in accordance with our choice of technology [82]:

- The 34-meter Beam Waveguide (BWG) antenna DSS-25 in Goldstone
- The 34-meter Beam Waveguide (BWG) antenna DSS-34 in Canberra
- The 34-meter High Efficiency (HEF) antenna DSS-65 in Madrid

The characteristics of the antennas are given in Table 6.2 and their locations are represented on Figure 6.1.

Those three ground stations are grouped into one constellation so that when the communication link between the ground segment and the architecture is computed, STK considers the ground segment as one element and considers the link availability as continuous if the reception of the signal switches from one ground station to another.

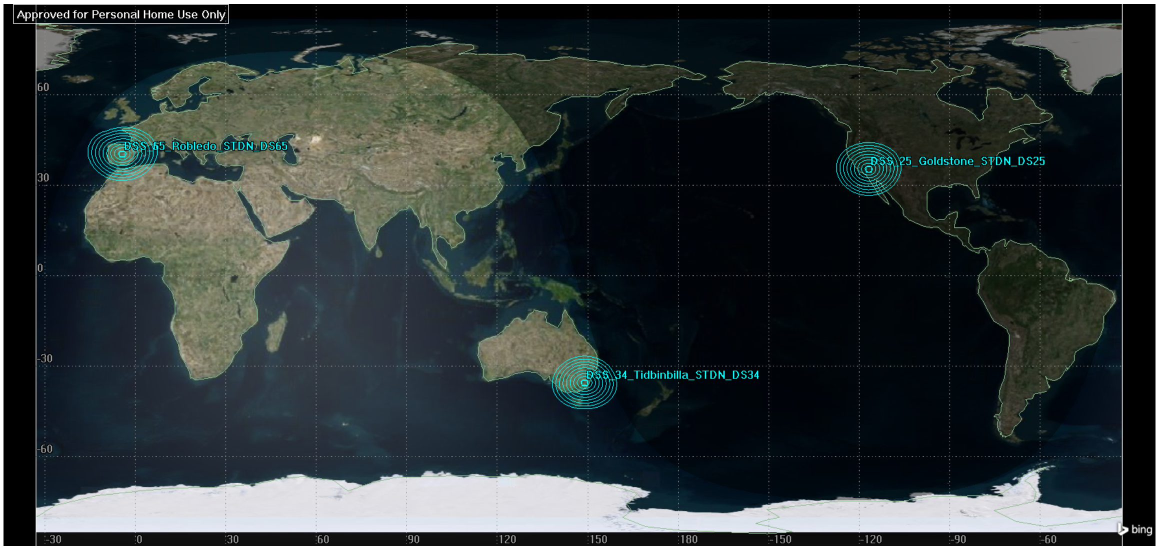


Figure 6.1: Location of the NASA DSN antennas selected in the framework

6.1.2 The architectures

The environment is the same for each architecture. It is uploaded before each architecture implementation. Then the architecture is added to that environment. The architecture is composed of one or several satellites. For each satellite, the correct central body (generally the Sun or Mars) has to be defined when the satellite is added. The orbit of the satellite is propagated using Astrogator in STK. This is the only propagator internal to STK that enables the implementation of all the kind of orbits needed here (heliocentric, around Mars, halo orbits etc). It also enables the setting into orbit of the satellite from the launch from Earth to the final orbit and the computation of the propulsive maneuvers required to maintain the satellite on its orbits. These capabilities could be used in future work to have a more complete simulation and assessment of the architecture.

Once the propagator is selected, the initial state of the satellite is defined in the inertial coordinate system if the central body selected. The orbit is given by its orbital elements referred as the coordinate type "Keplerian" in STK. The orbit is propagated using a two-body model. This means that only the gravitational force exerted by the central body is considered. The planet is viewed as a point mass, that means that the perturbation of the magnetic field of the planet (for example the J2-perturbation for the Earth) is not taken into account.

Finally, the influence of the different technologies is not considered but the solar exclusion angle has to be implemented to evaluate the architectures with respect to the link availability. It can be directly set in the properties of the satellites. As we assume a X-band technology, the value is set to two degrees.

Just as the ground stations are grouped into a constellation, the satellites around Mars are grouped into a constellation too. If there are several satellites that play the role of the relay and not used at the same time but alternatively in according to their relative positions with the Earth and Mars they are also grouped in a constellation.

6.2 Defining the metrics

Once the framework is built and the architectures implemented, it is used to evaluate the architectures. There is a need to define the metrics that evaluate the architectures with respect to each requirement. In the following section, those metrics are referred as the metrics or the outputs of the framework. The way to evaluate an architecture with respect to each metric is also described. In this study, five requirements are considered, describing the essence of the problem: the link availability, the coverage, the propagation delay, the data rate and the number of satellites. In the following, each of these requirements is discussed to understand its origin and define the associated metrics used to evaluate the architectures.

6.2.1 Link availability

The first goal of the architecture is to provide a continuous communication link between the Earth and Mars. As seen in the "Motivation" Chapter, the main obstacle is the interruption of the communication link during solar conjunction events, when the Earth, the Sun and Mars are aligned. This event occurs every synodic period. As a result, our scenario

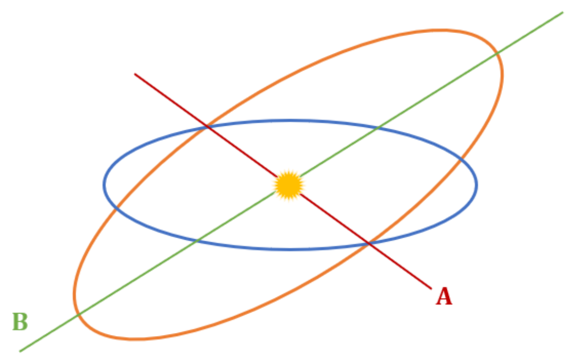


Figure 6.2: Worst-case scenario for the link availability

has to span over 780 days. The geometry repeat itself about every fifteen years. We want to simulate the worst-case scenario. Because the inclination of the Earth's orbit and the Mars' orbit, some solar conjunctions are better than others in terms of link interruption. As illustrate on Figure 6.2, it is better if the two planets are aligned on a line perpendicular to the intersection of the plane of each planet (green line on the Figure) than on the intersection of the two planes (red line on the Figure). According to [29], the worst-case scenario between 2015 and 2026 occurs in November 2023. Thus, our scenario spans from November 1, 2022 and December 20, 2024.

In the "Motivation" Chapter, it has been seen that the interruption of the link depends on what is called the exclusion angle. This exclusion angle depends on the frequencies of the signal. As we do not model the communication technology in this study, we set this exclusion angle to 2 degrees for all the satellites in all the architectures. It corresponds to the value for the X-band [27].

The requirement on link availability is 100%. The metrics associated with this requirement is the percentage of time there is an access between the ground segment on Earth and Mars during one synodic period. The ground segment on Earth is the constellation of the three facilities of the NASA DSN. This metric is called "**access**" and is a percentage.

To evaluate the architectures with respect to this metric, a chain is created between the ground segment on Earth and the satellite constellation on Mars (the one from the architecture or the three-satellite areosynchronous constellation). This chain contains the relays or the heliocentric constellation in between the Earth and Mars if there are some. The value for the access is obtained by computing the accesses for the chain in STK. Once the accesses are computed, a report called "Complete Chain access" is generated. This report gives the number of seconds there is access over the time of the scenario, 780 days in this study. This value is converted into a percentage.

6.2.2 Coverage

The second goal of the architecture is to be suitable for all the robotic and manned missions in the future. As we are not able to predict the area of interest on Mars for the next fifty years, we want a complete coverage of the planet. To assess the architecture, the coverage of the planet is computed over one day only, from October 10, 2023 at 00:00 UTGC to 11 October 2023 at 00:38 UTGC.

The metric associated with this requirement is the percentage of the surface covered. It is called "**mean coverage**" and it is a percentage.

To evaluate the architectures with respect to this metric a "Coverage Definition" element is added in STK. The coverage is computed over all the surface of Mars, from latitude -90 degrees to +90 degrees. The granularity of this coverage definition is set to 5 degrees for both the latitude and the longitude. This granularity is chosen to have a good compromise between the accuracy of the results and the computational time. The coverage definition is illustrated on Figure 6.3. The surface of Mars is divided into 182 areas, each area has 9 points of computation, that gives 1 638 points of computation. To get the value for the mean coverage, the accesses for the Coverage Definition element have to be computed. Then, the "Percentage Coverage" report gives the mean coverage over the length of the scenario.

6.2.3 Propagation delay

As seen in the "Background" Chapter, the electromagnetic waves used to propagate the communications move at the speed of light c. Thus, the propagation delay is directly related

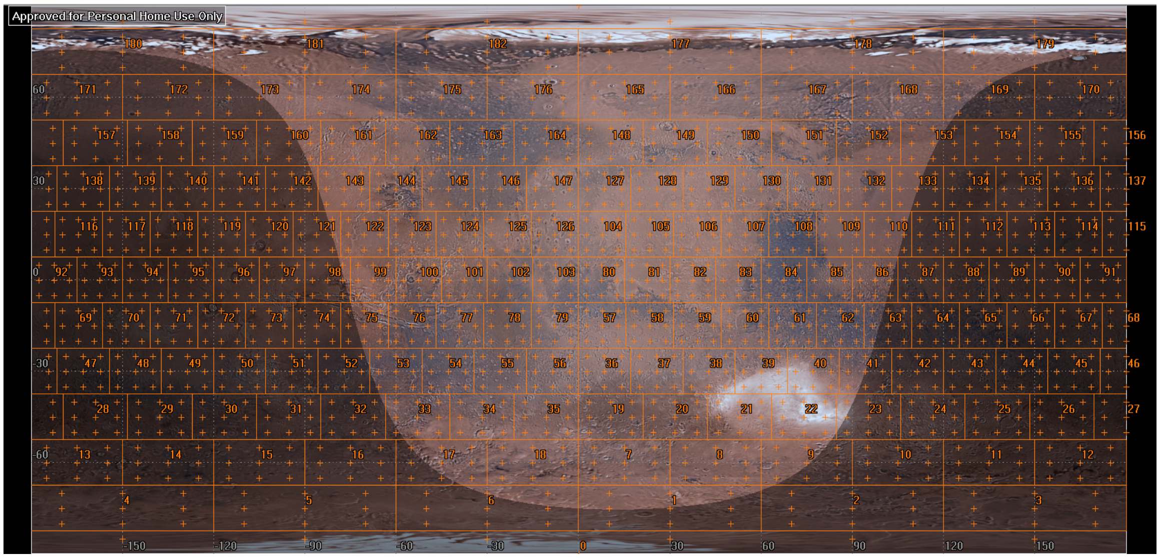


Figure 6.3: Definition of the coverage

to the end-to-end distance using the Equation 6.1.

$$t = \frac{d_{tot}}{c} \tag{6.1}$$

To obtain the propagation delay, the shortest end-to-end distance between the ground segment and Mars in the worst-case scenario is computed. Then this distance is divided by c. As the relationship between d_{tot} and t is linear, the metric considered is d for the sake of simplicity

The metric associated is called the "**delay**". It is a distance in kilometers.

To evaluate the architectures with respect to this metric, the chain between the Earth and Mars created to assess the link availability is used. This time, an "Access AER" report is generated. It gives the end-to-end range. The maximum value of this parameter is our delay.

6.2.4 Number of elements

This requirement is set to have a very high-level idea of the complexity and thus the resulting cost of the overall architecture. Indeed, it might be better in terms of performance and coverage to put a lot of satellites around Mars and in heliocentric orbits, but such a solution is not feasible due to a high cost. The metric associated is "**number of elements**". It is a number. It is directly given in the definition of the architecture.

6.2.5 Data rate

The work produced at Step 1, shows that the data rate varies with the choice of the communication technology and is independent from the architecture. Without considering the choice of the technology, the assessment of the communication performance is lost, which is not a problem given that the aim of the study is to demonstrate a methodology and not to provide a complete and exhaustive assessment of the Earth-Mars communication architectures. However, the requirement on the number of elements have been added to balance the performance. If the data rate requirement is withdrawn, the evaluation is unbalanced again. To have a trade-off with the number of elements, the choice has been made to introduce a notion of power received. It substitutes the data rate.

In Step 1, it is highlighted that the data rate is a function of the size, frequency and power of the transmitter and the BER (Bit Error Rate) required in reception. In free-space, the power received can be approximated using the following Equation [83]:

$$P_r \cong \left(\frac{P_t}{R}\right)^2 \tag{6.2}$$

Pr is the power received, Pt is the power transmitted and R is the range between the transmitter and the receiver. By transitivity, increasing the data rate requires more power, thus is reduces the distance between the transmitter and the receiver if those two latter elements are unchanged. Thus, considering the distance between two elements is a good substitute to the data rate.

The metric associated with the power is the square of the maximum distance between two elements of the architecture. It is a squared distance in km^2. The metrics associated is called "**energy**". This metric is interesting to trade with the number of elements as the more elements you put, the less space you have between two elements. This trade is particularly satisfying for the architectures with a relay. For a constellation architecture, the distance between the Earth and Mars is the driving distance so.

To evaluate the architectures with respect to those metrics, a vector between each pair of two elements its created. The norm of the vectors can be extracted over one synodic period. The maximum norm of all vectors during the period is the result used here.

6.3 Validating the framework

Before, evaluating the architectures, the framework and the way to compute the metrics have to be validated to ensure the accuracy of the results. Two validations are performed here.

1. The first validation is based on the IRIS architecture. IRIS has been implemented in STK by the authors of the project to compute the link availability between the DSN and their constellation of aerosychronous around Mars. This first test case is used to validate our way to implement the architectures in STK and the way to compute the access metric [84].

2. The second validation is based on the MarsWeb architecture. The authors of this architecture provide results on the coverage: a full and continuous coverage outside the solar conjunction events. This second test case is used to validate the mean coverage and the full coverage area [45, 51].

6.3.1 IRIS Test case

Presentation of the test case

IRIS Mars Communication Network is a communication architecture between the Earth and Mars designed by a team of students from the University of Central California in re-

Table 6.3: Orbital elements of the IRIS Test case

Satellite	Semimajor axis	Eccentricity	Inclination	Argument of periapse	RAAN	True anomaly
IRIS I	20431	0	0	0	0	215.7
IRIS II	20431	0	0	0	0	95.7
IRIS III	20431	0	0	0	0	335.7

sponse to a competition organized in 2015 by the SSPI (Space & Satellite Professionals International). The competition was called "Satellites around Mars". Its goal was to propose a feasible and reliable satellite communications network to provide a 98% continuous communication between the Earth and Mars.

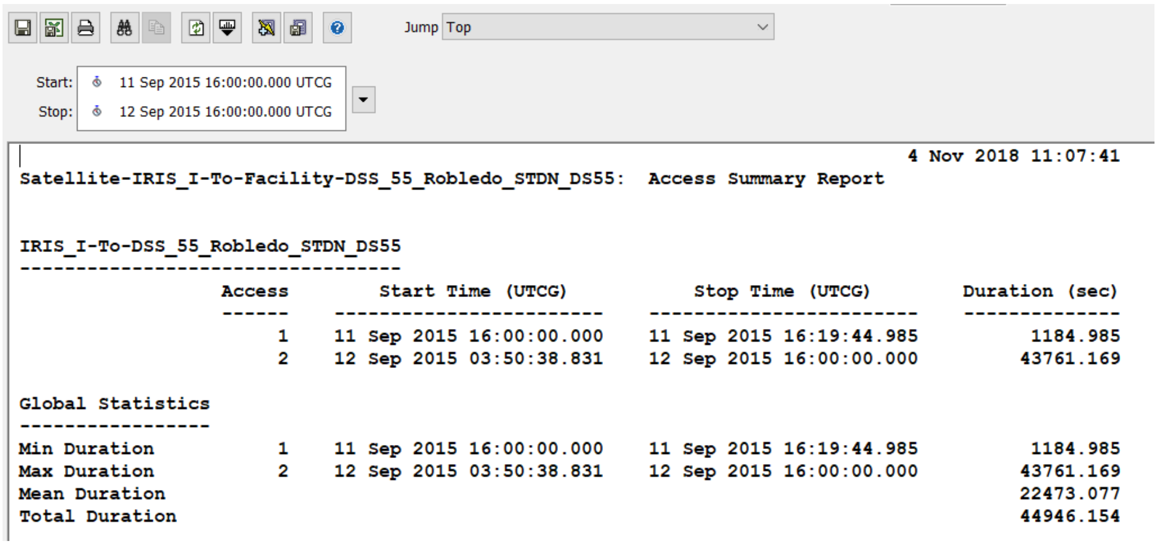
The solution selected by the team is a constellation of three areosynchronous satellites around Mars equally distributed on the equator plane. The three satellite locations are:

- IRIS I: 0 degrees North, -13.5 degrees West
- IRIS II: 0 degrees North, -132.5 degrees West
- IRIS III: 0 degrees North, 107.5 degrees East

The corresponding orbital elements are given in Table 6.3 as of September 11, 2018.

This scenario contains information that enable us to validate the way we implement our architecture as the report specifies the ground segment used and the time of the simulation. The ground segment for this architecture is composed of four stations of the NASA DSN:

- DSS25 (34m Beam Waveguide (BWG). Uplink (X, Ka), Downlink (X, Ka)) in Goldstone, California,
- DSS26 (34m Beam Waveguide (BWG). Uplink (X), Downlink (X)) in Goldstone, California,
- DSS34 (34m Beam Waveguide (BWG). Uplink (S, X), Downlink (S, X, Ka)) in Canberra, Australia,


Jump Top

Start: 11 Sep 2015 16:00:00.000 UTCG

Stop: 12 Sep 2015 16:00:00.000 UTCG

4 Nov 2018 11:07:41

Satellite-IRIS_I-To-Facility-DSS_55_Robledo_STDN_DS55: Access Summary Report

IRIS_I-To-DSS_55_Robledo_STDN_DS55

	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
	1	11 Sep 2015 16:00:00.000	11 Sep 2015 16:19:44.985	1184.985
	2	12 Sep 2015 03:50:38.831	12 Sep 2015 16:00:00.000	43761.169

Global Statistics

Min Duration	1	11 Sep 2015 16:00:00.000	11 Sep 2015 16:19:44.985	1184.985
Max Duration	2	12 Sep 2015 03:50:38.831	12 Sep 2015 16:00:00.000	43761.169
Mean Duration				22473.077
Total Duration				44946.154

Figure 6.4: Our access results for the IRIS Test case

- DSS65 near Madrid in Spain (34m HEF (High Efficiency), Uplink X, Downlink X and S). The antennas are 34-meter high gain antennas.

The simulation period is over one sidereal day, from 11 September 2015 16:00:00 UTCG to 12 September 2015 16:00:00 UTGC.

Validation

Once the architecture is implemented and the access between the ground segment and the Martian constellation is computed, the Complete chain access report is generated. The report we obtain is given on Figure 6.4. A screenshot of the IRIS team's results is on Figure 6.5. As you can see, the results are the same to the second. This validates the framework and the way to compute the link availability.

The implementation of the IRIS Test case in STK is presented on Figure 6.6.

```
                                                                        11 Sep 2015 00:31:13
Approved for Personal Home Use Only
Satellite-Satellite1-To-Facility-DSS_55_Robledo_STDN_DS55:  Access Summary Report


Satellite1-To-DSS_55_Robledo_STDN_DS55 - Satellite1-To-DSS_25_Goldstone_STDN_DS25
--------------------------------------------------------------------------------
                  Access        Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                  ------    ------------------------    ------------------------    --------------
                       1    11 Sep 2015 16:00:00.000    11 Sep 2015 16:19:45.253          1185.253
                       2    12 Sep 2015 03:50:39.109    12 Sep 2015 16:00:00.000         43760.891

Global Statistics
-----------------
Min Duration           1    11 Sep 2015 16:00:00.000    11 Sep 2015 16:19:45.253          1185.253
Max Duration           2    12 Sep 2015 03:50:39.109    12 Sep 2015 16:00:00.000         43760.891
Mean Duration                                                                            22473.072
Total Duration                                                                           44946.143
```

Figure 6.5: Given access results for the IRIS test case

6.3.2 MarsWeb Test case

Presentation of the test case

The MarsWeb alternative has been developed in 2007 by a seven-student team for Politecnico di Milano. The intent is to develop an Earth-Mars communication architecture to support all the possible activities on Mars, including a manned mission. The requirements they set on their mission regarding the communication purpose are the following:

- A data rate of at least 500 kbps
- A complete coverage of the surface of the planet (all the latitude covered)
- A continuous coverage of the surface of the planet (minimization of the black-out periods)

The MarsWeb architecture is composed of eight satellites, distributed on two orbital planes inclined of 37 degrees over the equator with a difference in Right Ascension of the Ascending Node (RAAN) of 180 degrees. On each plane, only three satellites are used for communication purpose. They are located at an altitude of 17030 km. The fourth satellite is located on an orbit 1240 km above and is there to ensure redundancy in case of the failure of one of the three initial satellites. In our scenario, we are evaluating the communication performances of the architecture. The redundancy and reliability requirements are not

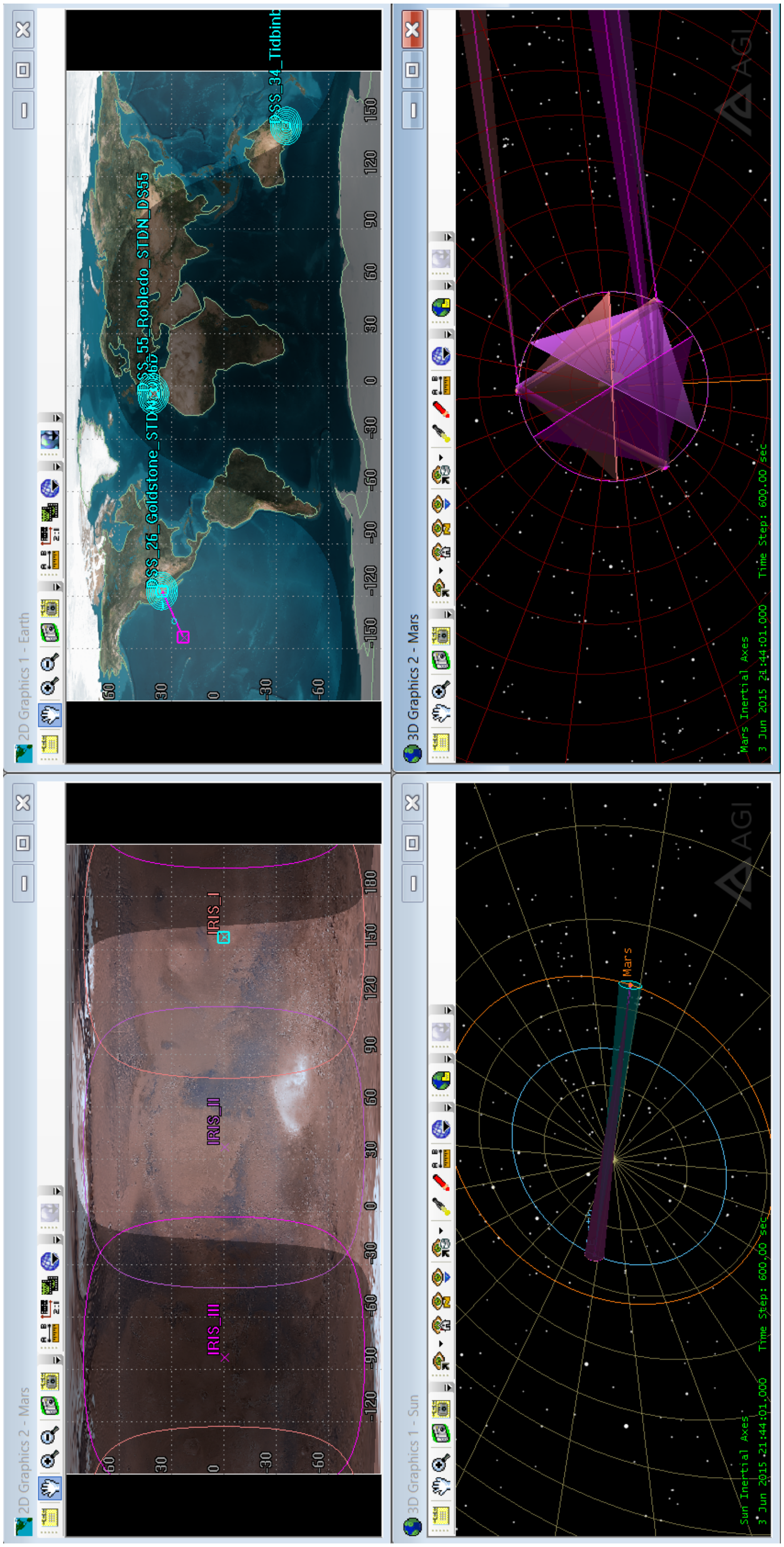


Figure 6.6: IRIS test case

Table 6.4: Orbital elements of the MarsWeb Test case

	Semi-major axis	**Eccentricity**	**Inclination**	**Argument of periapse**	**RAAN**	**True anomaly**
1	20431 km	0	37 deg	0 deg	0 deg	0 deg
2	20431 km	0	37 deg	0 deg	0 deg	120 deg
3	20431 km	0	37 deg	0 deg	0 deg	240 deg
4	20431 km	0	37 deg	0 deg	180 deg	5 deg
5	20431 km	0	37 deg	0 deg	180 deg	125 deg
6	20431 km	0	37 deg	0 deg	180 deg	245 deg

considered. Therefore, we will consider only three satellites per plane in the implemented architecture. The orbital elements of the six satellites are given in Table 6.4.

Validation

As the satellites are areosynchronous the period corresponds to one Martian day. The period of the orbit is about 24 hours and 38 minutes. By simulating the architecture over two days, the value will be the same for the mean coverage and the full coverage area as for the entire synodic period.

The beginning and the end of the percentage coverage report are given on Figure 6.7 and Figure 6.8 respectively. These two figures illustrate the type of report that can be generated by STK. The coverage by latitude report is given on Figure 6.9. The coverage is at 100% at any time and all the latitudes are fully covered as illustrated at the end of the coverage report on Figure 6.8. The results are the same as those given by the authors of the paper. Besides, by generating an access report, the total duration of access is 65,624,014 s, that is to say about 759 days. The synodic period is of 780 days. That means that the link is not available for about 21 days. This is the value predicted by several studies for the use of the X-band frequency [27].

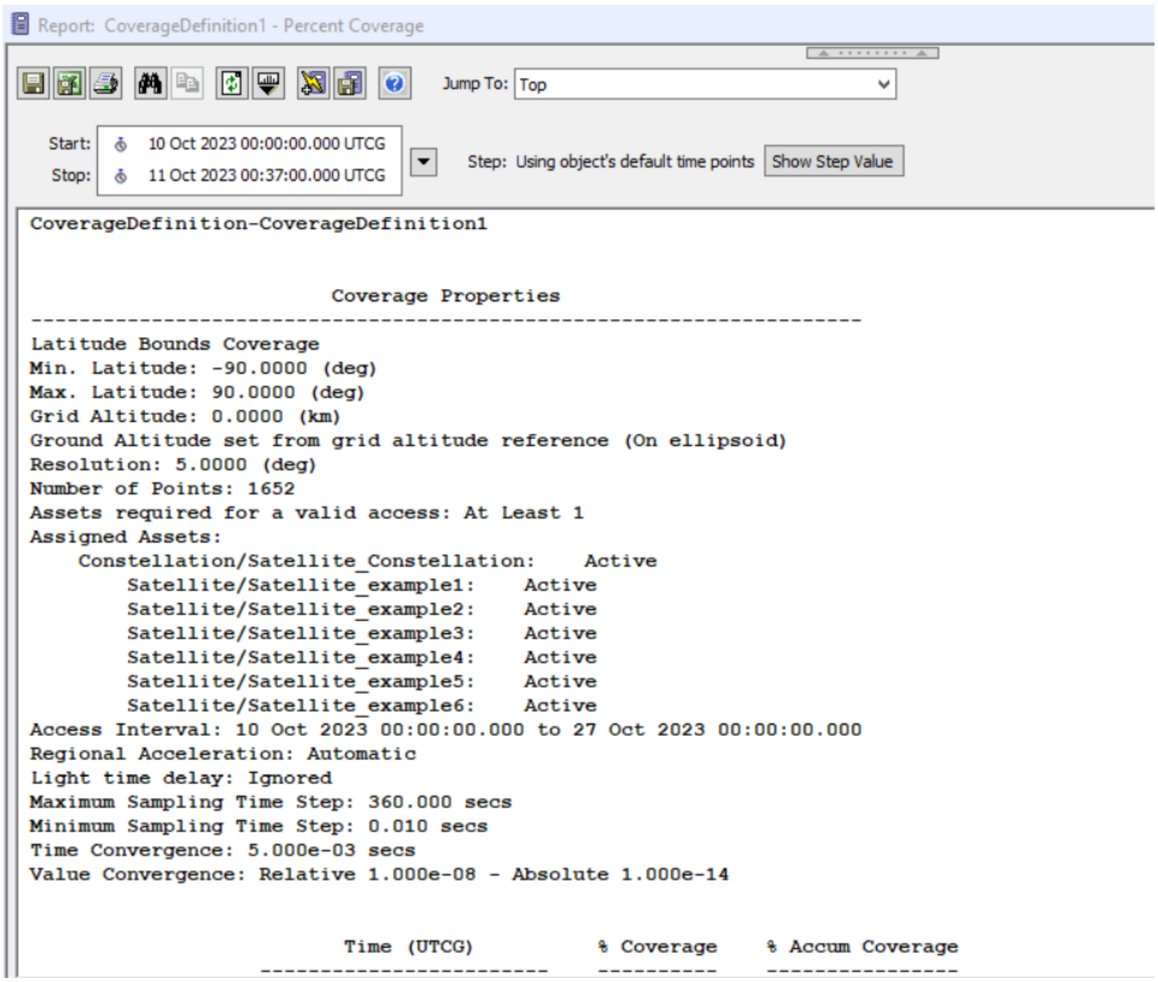


Figure 6.7: Beginning of the MarsWeb coverage report from STK

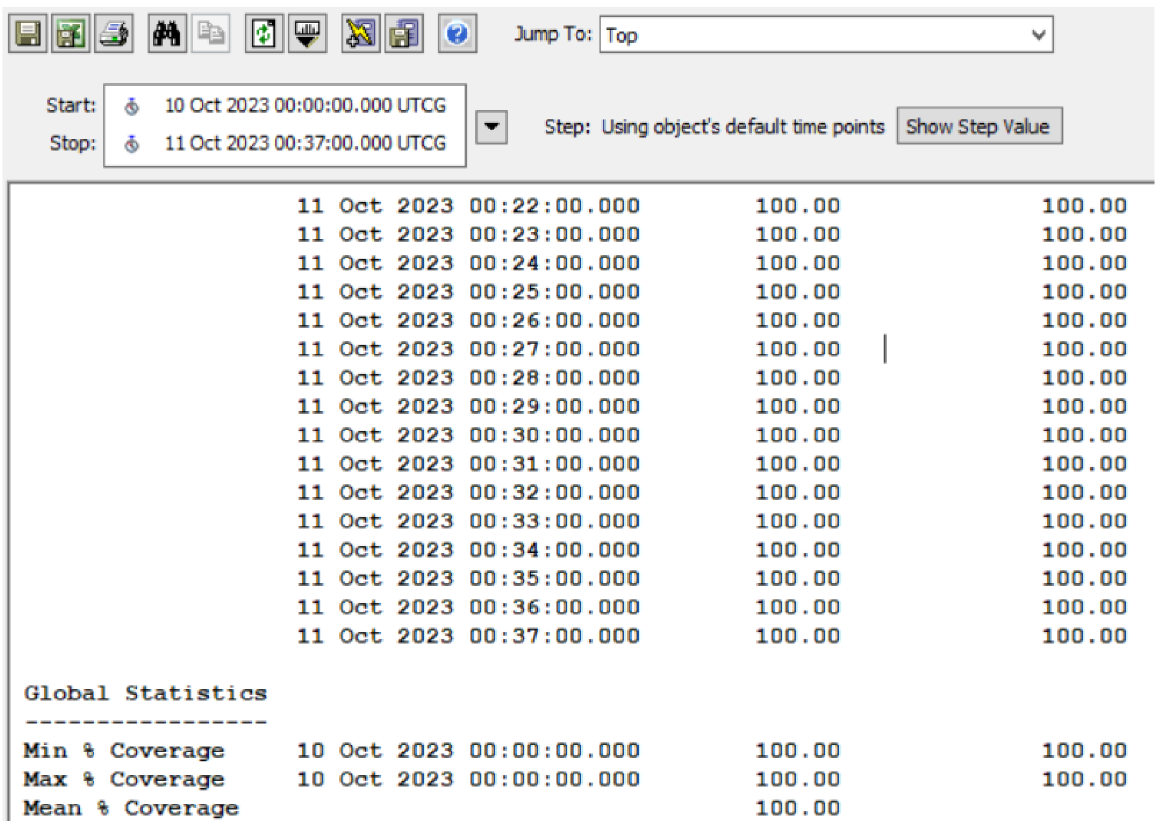


Figure 6.8: End of the MarsWeb coverage report from STK

Latitude (deg)	Percent Time Covered	Total Time Covered (sec)
-90.000	100.00	1468800.00
-85.000	100.00	1468800.00
-80.000	100.00	1468800.00
-75.000	100.00	1468800.00
-70.000	100.00	1468800.00
-65.000	100.00	1468800.00
-60.000	100.00	1468800.00
-55.000	100.00	1468800.00
-50.000	100.00	1468800.00
-45.000	100.00	1468800.00
-40.000	100.00	1468800.00
-35.000	100.00	1468800.00
-30.000	100.00	1468800.00
-25.000	100.00	1468800.00
-20.000	100.00	1468800.00
-15.000	100.00	1468800.00
-10.000	100.00	1468800.00
-5.000	100.00	1468800.00
0.000	100.00	1468800.00
5.000	100.00	1468800.00
10.000	100.00	1468800.00
15.000	100.00	1468800.00
20.000	100.00	1468800.00
25.000	100.00	1468800.00
30.000	100.00	1468800.00
35.000	100.00	1468800.00
40.000	100.00	1468800.00
45.000	100.00	1468800.00
50.000	100.00	1468800.00
55.000	100.00	1468800.00
60.000	100.00	1468800.00
65.000	100.00	1468800.00
70.000	100.00	1468800.00
75.000	100.00	1468800.00
80.000	100.00	1468800.00
85.000	100.00	1468800.00
90.000	100.00	1468800.00

Figure 6.9: Coverage by latitude for MarsWeb from STK

6.4 The architectures survey

The framework is built and ready to receive the architectures. The metrics are defined. In this section, the survey of the communication architectures between the Earth and Mars is presented along with some screenshots of the implementation in STK. The complete description of the architectures can be found in Appendix. In the appendix, the architectures are classified by type and ranked by date. The following information are specified for each architecture:

- the code of the architecture that is used as a reference for the implementation and the evaluation of the architecture,
- the name of the architecture with a brief description,
- the reference of the paper associated with the architecture,
- the date,
- the number of satellites,
- the orbital elements of each satellite or the description of the location of the satellites.

The list of architectures is intended to be as exhaustive as possible. It has to be noticed that many papers refer to the same architecture, in particular to areosynchronous constellations, relays at Lagrangian points or the MarsSat concept. In this case, all the references may not be cited in the line corresponding to the architecture.

The architectures presented in the survey are classified by type. The code of each architecture starts with a letter that corresponds to its type. There are four types of architectures:

1. the Martian constellation (code starting with "A") that includes the Martian navigation constellations (code starting with "B")
2. the heliocentric concepts having several satellites in heliocentric orbit (code starting with "C"),

3. the relays (code starting with "E") and
4. the mixed architectures that are combinations of satellites from at least two of the three previous categories (code starting with "D").

The classification is slightly different from the one proposed in the "Background" Chapter. In the "Background" Chapter, the intent was to show the wide range of existing concepts and to point out the advantages and disadvantages of each configuration. The architectures were classified according to their location, advantages and disadvantages. Here, the architectures are intended to be implemented and evaluated. They are classified according to their functions regarding the requirements (constellations ensure a complete coverage while not overcoming the days of black-out during the solar conjunction events, relay overcome the problem of solar conjunction events etc). In the following, the main concepts of each category are described.

The non-keplerian concepts are excluded from the survey because of the non-classical orbital mechanics used in these concepts. They employ low-thrust propulsion systems to force the spacecraft out of a natural Keplerian orbit [85, 86, 87].

6.4.1 Martian constellations

The first type is the Martian constellations. A Martian constellation is defined as an architecture with at least two satellites, the satellites being in orbit around Mars. The subsection first reviews two particular Martian constellation: the areosynchronous constellation and the Draim constellation. Then, the two main categories of constellations are presented. It is concluded by the introduction of navigation constellations.

areosynchronous constellations

The aerosynchrnous constellation is the oldest design of constellation around Mars, introduced by Palamarik in 1989 [88]. The concept is the same as geosynchronous satellites.

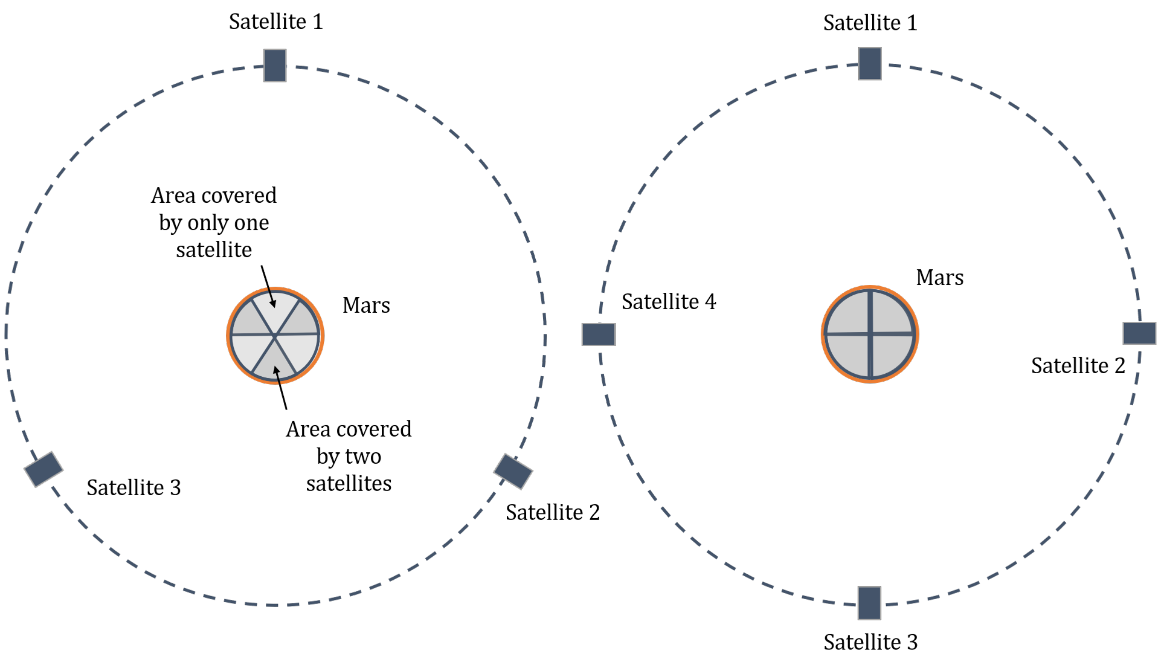


Figure 6.10: Difference of coverage with a three-satellite configuration versus a four-satellite configuration

Several satellites, usually three (architecture **AO**) or four (architecture **AC**), orbit around Mars on its equatorial line at the same angular velocity as Mars. The semi-major axis a of the orbit is given by the period and the gravitational parameter of Mars following the equation:

$$T_{Mars} = 2\pi\sqrt{\frac{a^3}{\mu_{Mars}}} \tag{6.3}$$

the Martian period T_{Mars} is 24.623 hours and its gravitational parameter μ_{Mars} is $43,800\ km^3/s^2$ [28]. That gives a semi-major axis a of 20,431 km [88].

The benefit of an areosynchronous network is that there is no nodal regression effect as is the case with inclined orbits. Nodal regression reduces the surface covered. The important limitation of such a network is the weak coverage of polar regions. The minimum number of satellites required to ensure a complete coverage is three, it is the IRIS architecture **AO** [84]. However, it is better that each point of the surface is covered by at least two satellites for the sake of redundancy. As seen in Figure 6.10, this condition is satisfy with four satellites [6]. It is architecture **AC**

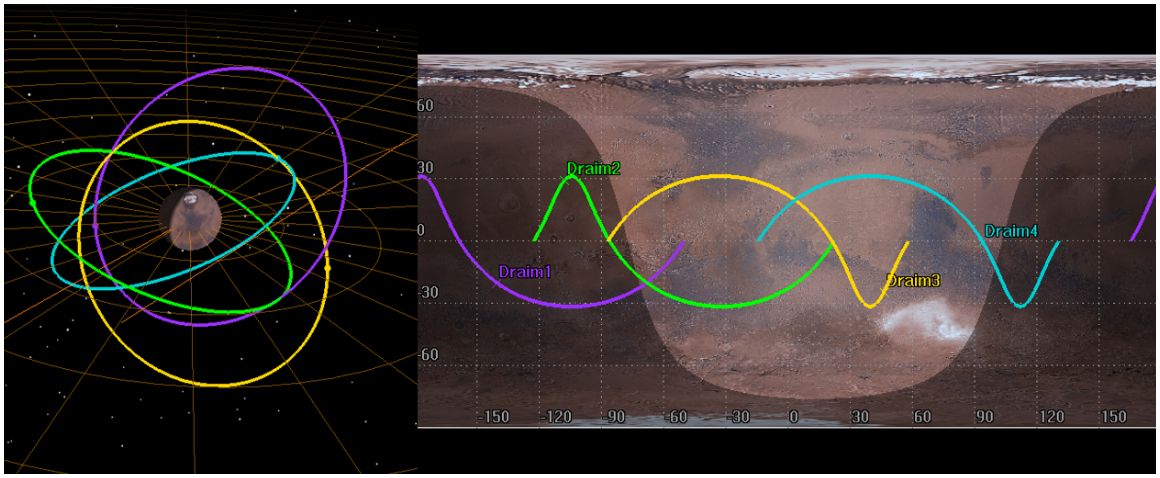


Figure 6.11: Implementation of the Draim constellation in STK

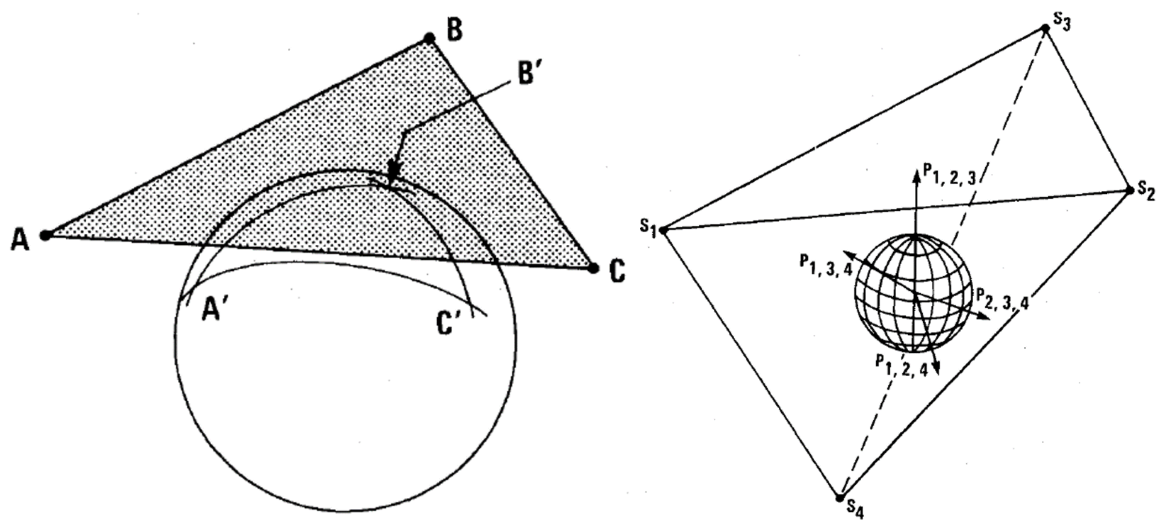
Draim constellation

Another particular design is the Draim constellation. In 1984, J. Draim proved that the minimum number of satellites required to fully cover the Earth is four [89]. The same theorem can be applied to Mars with a few modifications. The Draim constellation around Mars implemented in STK is presented on Figure 6.11. Its code is **AB**. The concept is based on one theorem and one corollary [90]:

- "Theorem I: If a plane containing three satellites does not intersect the Earth or if this plane is tangent to the Earth at some point, then every point within the spherical triangle on the Earth's surface formed by the satellites'suborbital points is visible from at least one of the satellites." (Figure 6.12a)

- "Corollary II: If the Earth is completely enclosed within a tetrahedron formed by four planes (each containing three satellites), then any point on the Earth's surface is visible from at least one of the satellites, by successive use of theorem I." (Figure 6.12b]

Thus, a complete coverage is ensured by a four-satellite constellation as long as the planet is inside the tetrahedron formed by the satellites at all times. The orbits satisfying this condition are four elliptic orbits with the same period, the same eccentricity and the same



(a) Theorem 1 (b) Corollary 2

Figure 6.12: Illustration of the theorem and the corollary supporting the Draim constellation design [90]

Table 6.5: Orbital elements of the four-satellite network [90]

	i (degree)	**e (unitless)**	**ω (degree)**	**Ω (degree)**	**M (degree)**
Satellite 1	31.3	0.263	-90	0	0
Satellite 2	31.3	0.263	+90	90	270
Satellite 3	31.3	0.263	-90	180	180
Satellite 4	31.3	0.263	+90	270	90

inclination, as illustrated Figure 6.13. The orbital elements are given Table 6.5. i is the inclination, e is the eccentricity, ω is the argument of periapse, Ω is the right ascension of ascending node and M is the mean anomaly. The definition of the orbital elements is given in Figure 6.14.

The benefit of this constellation is that it provides a global coverage at all times with only four satellites. Besides, the four satellites have the same characteristics. To ensure redundancy a fifth satellite is required. The main drawback is that these satellites required important station keeping compared to other options.

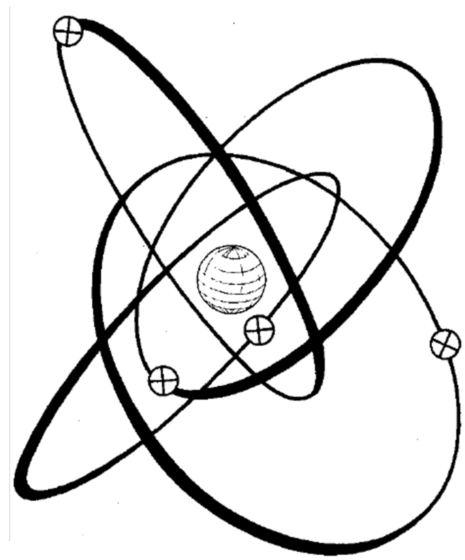


Figure 6.13: Common-period four-satellite network [90]

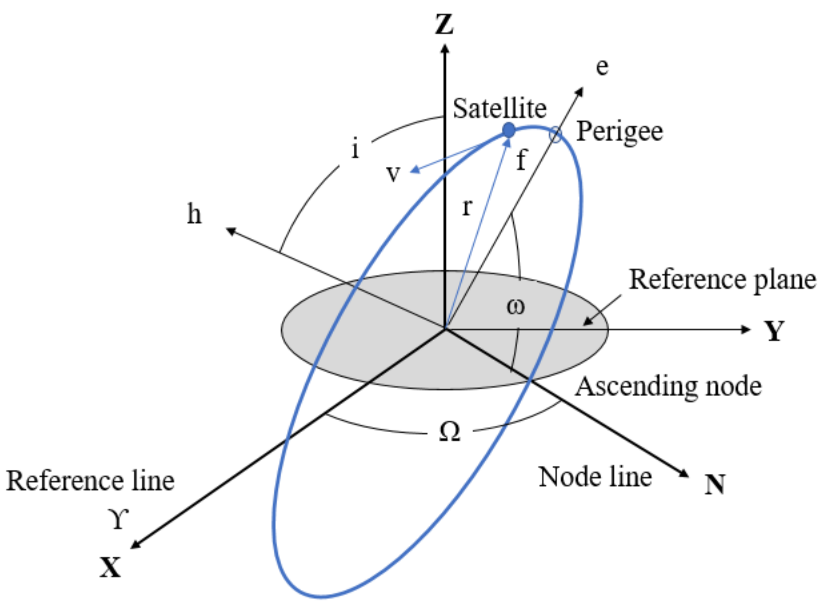


Figure 6.14: Definition of the orbital elements

General considerations on constellations

Martian constellation design is a long-lasting topic of research that started in the 1980's. Up to recently, most designs were restricted to areosynchronous networks and constellation of circular orbit satellites. In the last years, new designs, such as Walker constellations and Flower constellations [44], have revolutionized constellations design. Also, the development of CubeSats for deep-space applications is expected to open the path for new opportunities. CubeSats are nanosatellites composed of one or several $10 \times 10 \times 10$ cm cubic units, each unit weighting no more than 1.33 kg. There are low-cost satellites. They enable a constellation of many more satellites for the same cost, such as the 36-satellite constellation designed by Aviles et al. [91]. Cubesat efficiency has been proven in Earth orbit. MarCO is the first one to operate on Mars orbit, demonstrating CubeSat capabilities and long-range communication using X-band frequencies [92]. As mentioned, many constellations exist. They can be broken down into two categories [44]:

- Walker constellations: This is the classical constellation design. It is characterized by three integer parameters t, p and f, and three real parameters h, i and Ω. p is the number of planes, t is the number of satellites, f is the relative spacing between two adjacent satellites, h is the orbit height, i is the orbit inclination and Ω is the Right Ascension of the Ascending Node (RAAN) (Figure 6.14).

- Flower constellations: Visualized in the Earth-Centered Earth-Fixed (ECEF) referential, the orbits draw a flower. Also, every satellite covers the same repeating track. A Flower constellation is characterized by six integer parameters: N_p the number of petals, N_d the number of days to repeat the track, N_s the number of satellites, F_n the phase numerator, F_d the phase denominator and F_h the phase step. The two first integers gives the semimajor axis of the orbit. Five other orbital elements have to be given for the first satellite to completely determine the constellation. The last three integers define the satellite distribution.

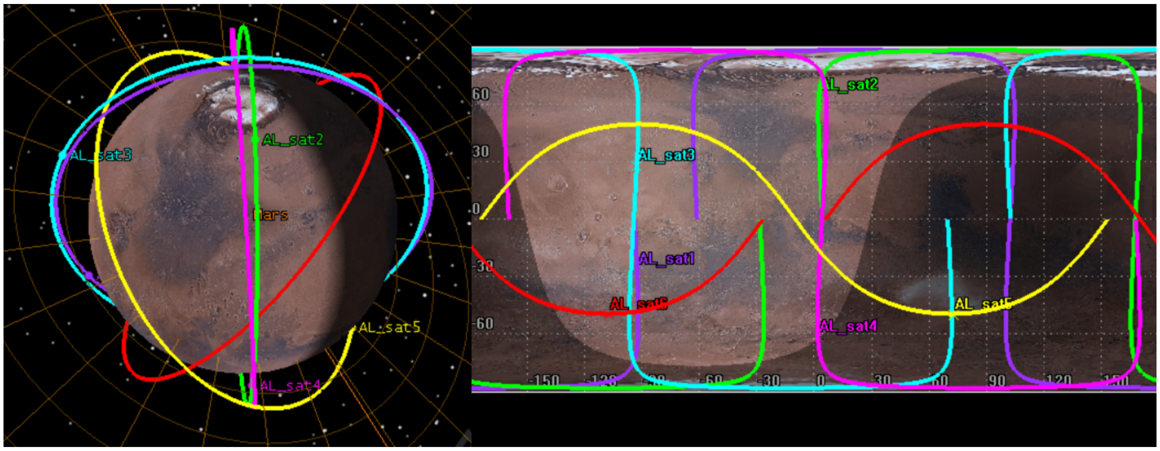


Figure 6.15: Implementation of the flower constellation **AL** in STK

A constellation design can be a combination of several Walker and/or Flower constellations.

Omitting the areosynchronous constellation and the Draim constellations, ten constellations can be distributed in those two categories. Architectures **AI**, **AJ**, **AK** and **AL** are Flower constellations compared by Sanctis et. al [44]. An example of flower constellation around Mars implemented in STK is presented on Figure 6.15. The other architectures are combinations of Walker constellations. These remaining architectures can be sub-divided into two categories:

1. the satellites in low orbits: architectures **AD**, **AE**, **AF** and **AG** compared by Bell et. al [42] and architecture **AH** offered by Cheung et al. [93],

2. the satellites in higher orbit: the MarsWeb architecture **AM** [51].

Navigation constellations

Two navigation constellations are taken into account in the survey, the architectures **BB** designed by Talbot-Stern [46] and **BC** offered by Kelly et al. [79]. The design of such a constellation is more constrained compared to a communication constellation. As explained in the "Background" Chapter, each point of the planet has to be covered by at least four satellites. The minimum number of satellites required to provide this navigation service is ten. The architectures **BB** and **BC** respectively have fifteen and twenty satellites.

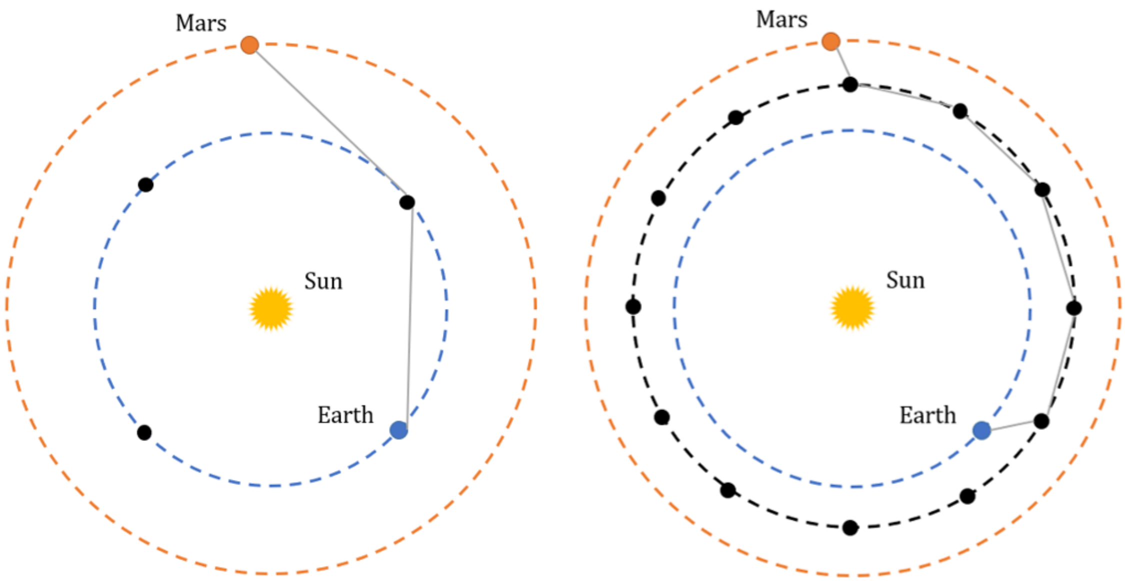


Figure 6.16: Heliocentric concepts (**CB** on the left, **CC** on the right)

It is much higher than the number of satellites required for a communication constellation (four), but an additional service is provided. Because of that, these constellation cannot be compared with other Martian constellations as the requirements and the constraints on the system are not the same.

6.4.2 Heliocentric concepts

The heliocentric concepts are defined as a network of two or more satellites on heliocentric orbits. The halo orbits around Lagrangian points L_1 or L_2 are excluded. These concepts are original compared to what we are used to find in the literature. There are two main concepts explained on Figure 6.16

The first concept **CB** offered by Howard et al. [94] is a constellation of three satellites Earth orbit distributed at +90 degrees, +180 degrees and +270 degrees from Earth. Depending on the relative position of the Earth and Mars, the communication link uses zero, one or two relays as illustrated on Figure 6.17.

The second concept **CC** by Goff [39] is a constellation of twelve satellites in circular orbit around the Sun. The radius of the orbits is 1.25 AU. This constellation has been spe-

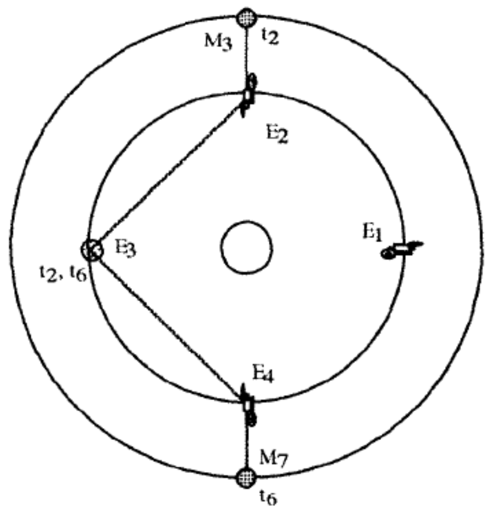


Fig 3.a: IPSAT Connectivity at t_2 and t_6

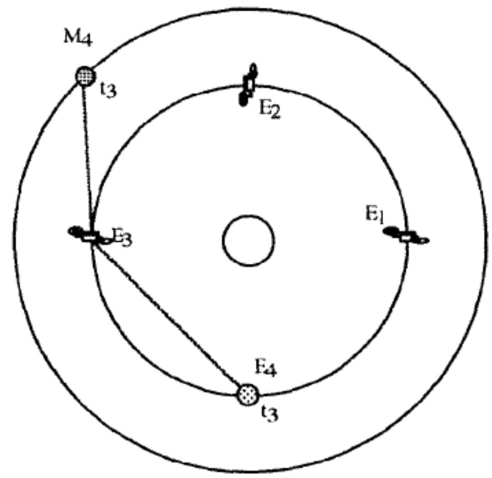


Fig 3.b: IPSAT connectivity at t_3

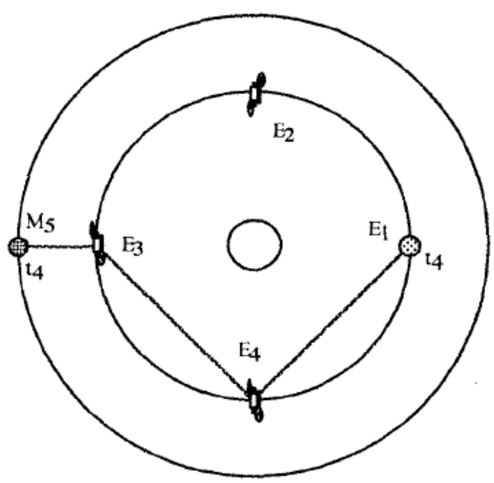


Fig 3.c: IPSAT Connectivity at t_4

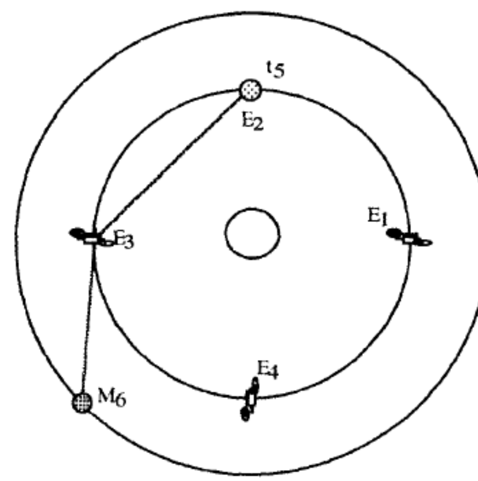


Fig 3.d: IPSAT connectivity at t_5

Figure 6.17: Architecture **CB** in different configurations

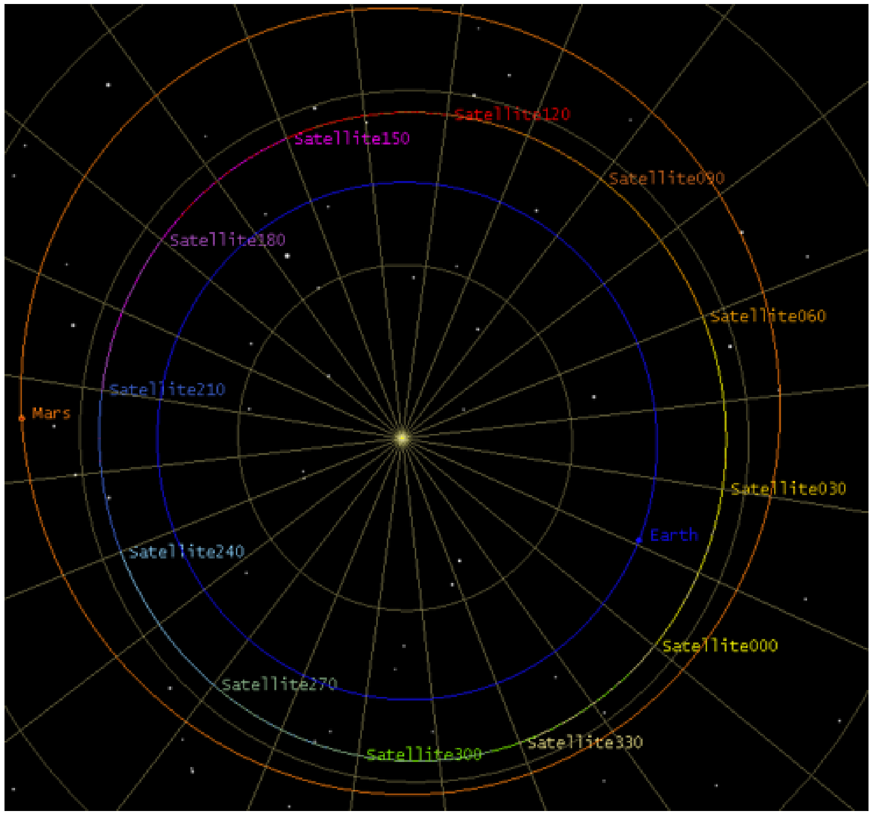


Figure 6.18: Implementation of the heliocentric concept **CC** based on FTL communications in STK

cially designed for the use of the FTL communication technology that required transmitters as close as possible to the midpoint between the two planets. Its implementation in STK is presented on Figure 6.18.

6.4.3 Relays

The third type is composed by the relays that already have been detailed in the "Background" Chapter. A relay is an architecture of one satellite whose the main goal is to ensure the link availability at all time. The architecture can be composed of a second satellite that is added for the redundancy and/or to ensure a better coverage of the red planet. Ten architectures of that type are considered in the survey. They are divided into four subcategories: the Lagrangian relays, the satellites on Mars orbit, the Gangale orbits and the cyclers.

Lagrangian relays

The Lagrangian points have been introduced previously. In the following section, the concepts using these points are depicted. In the survey, all the relays at Lagrangian points are in the Sun-Mars system. In the mixed architectures (next sub-section), some concepts include Lagrangian points in the Sun-Earth system.

The first and older design uses the stable points L_4 and L_5 points in the Mars-Sun system. This concept has been introduced by James Strong in 1972 [95]. There are two options for such a system: either it is used as an independent communication architecture, i.e. no other satellite is required to ensure a continuous and reliable communication between the Earth and Mars, or it is used with a constellation around Mars to overcome the solar conjunction issue. In the first option **EB**, two satellites are placed respectively in L_4 and L_5, as illustrated on Figure 6.19. The benefit of this solution is that, because those Lagrangian point are stable, no maneuvers are required to keep the satellite on its orbit. It greatly decreases the cost of the system and increases the lifetime. This solution has one main drawback: as seen in Figure 6.19, it does not ensure a complete coverage of Mars. The second option **EC** overcome this problem. The satellites at the Lagrangian points ensure one hundred percent link availability while the constellation enable a complete coverage. With a constellation around Mars, then only one satellite is required to overcome the solar conjunction issue [41, 50].

The second concept introduced in 1992 uses the instable points L_1 and L_2 in the Mars-Sun system. It is the architecture **ED**. This concept have been introduced by James Strong in 1972 [95]. In such design, two communication satellites are placed in halo orbits around the Lagrangian points L_1 and L_2, as shown on Figure 6.20. The two satellites are placed 180 degrees out of phase from each other in order to ensure a one hundred percent coverage of Mars. The benefits of this architecture are that only two satellites are required to ensure a complete coverage on the planet. The satellites are always in view of the Sun so they take advantage of the Sun at all times to power the system, allowing more power available

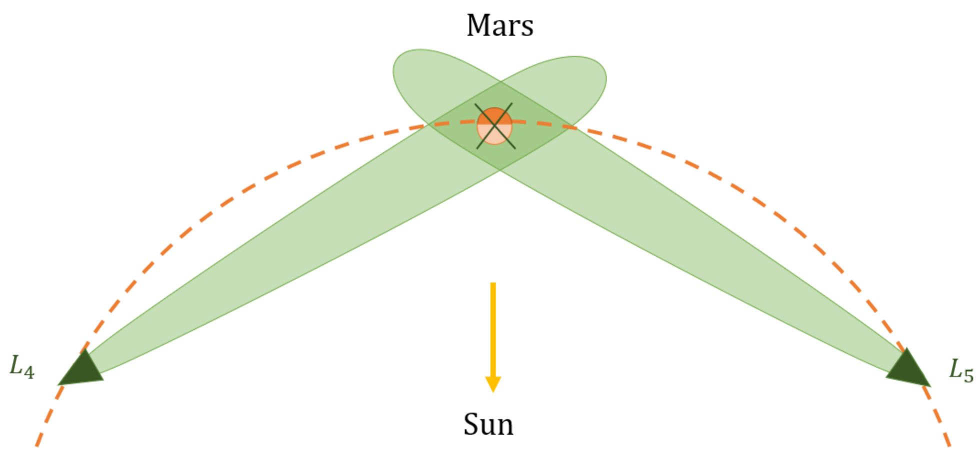


Figure 6.19: Satellites configuration around the stable Sun-Mars Lagrangian points

for communication transmission. The orbit is selected to avoid Solar exclusion zone and overcome the solar conjunction issue. This results in a 200,000 km out-of-plane amplitude [51, 47].

Leading/trailing relays

The second sub-category of relay is the leading (trailing) satellite. This satellite is placed on the Mars orbit but before (or after) Mars. Usually, the angle Satellite-Sun-Mars is about 20 degrees. The principle is the same as a halo orbit in L_4 or L_5. The benefit of this solution over the halo orbit is that the satellite is closer. Less power is required to ensure the communication between the satellite and Mars. Another point is that there is no risk of collision with an asteroid in the vicinity of the Lagrangian points. The main drawback is that the orbit is perturbed by the effect of the proximity with one of the Lagrangian points, L_4 for a leading satellite, and L_5 for a trailing satellite. Thus, more propellant is required to maintain the satellite on its orbit [50]. The concept with only one satellite leading Mars by 20 degrees is the architecture **EF**, the concept with the leading and the trailing satellites preceding/following Mars by 20 degrees is the architecture **EG**. Another option offered by Breidenthal et al. is one single satellite leading Mars by 10 degrees [48] - architecture **EJ**.

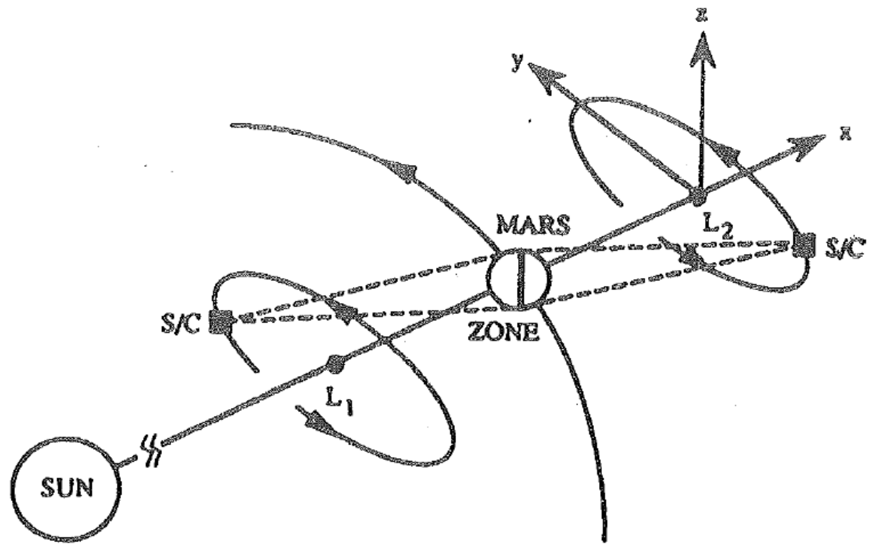


Figure 6.20: Satellites configuration around the instable Sun-Mars Lagrangian points [96]

Gangale relays

The third sub-category of relay is a family of orbits called Gangale orbits, named after its inventor. These orbits are characterized by the same orbital elements as the Martian orbit except that the eccentricity is a bit smaller and the orbit plane is a few degrees out of the Martian plane. That leads to a spacecraft that alternatively leads and trails Mars. From Mars, the satellite seems to orbit Mars, but in reality, it orbits the Sun. From Figure 6.21, "MarsSat (A) rises North of Mars, (B) trails, (C) drops South of Mars and (D) leads Mars" [97]. The original Gangale orbit has a Mars-Earth-satellite angle of 2.5 degrees and a distance Mars-satellite of 22 million kilometers. A certain number of alternatives exist with different eccentricities and different inclinations. There are various benefits to these orbits. The spacecraft alternatively leads and trails Mars. Thus, the impact of the Lagrangian points pulling the spacecraft from Mars, disappears. This reduces the amount of propellant needed to maintain the satellite on its orbit and thus the cost. As long as the inclination of the orbit is higher that the inclination of Mars' orbit, transmissions can go over the Sun and not just besides it. Furthermore, the distance Mars-satellite is the smallest compared to other relay options. The drawback is that there is still a need for station-

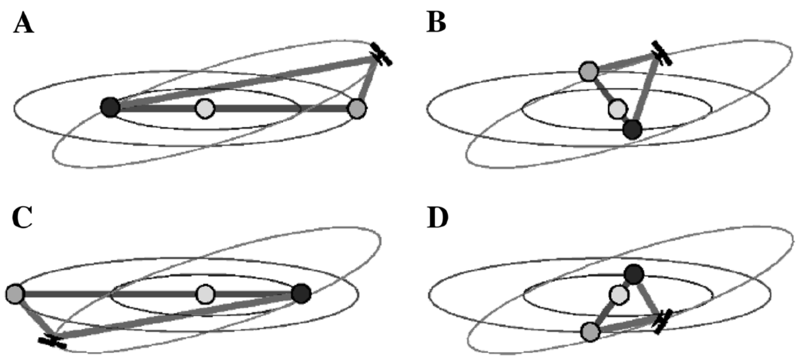


Figure 6.21: Gangale orbit [97]

keeping and thus a propellant cost (higher than for Lagrangian relays) [97, 50]. In the survey, the Gangale orbit derived is the one offered by Byford et al. as a good alternative as a communication relay. The orbit as the same eccentricity as Mars and is inclined by five degrees with respect to Mars [50]. The alternative with one satellite preceding Mars by 8 degrees is the architecture **EH**. The alternative with two satellites respectively preceding and following Mars by 8 degress is the architecture **EK**.

Cycler

Another particular concept of relay in heliocentric orbit is the cycler. Its primary purpose is not communication but rather the use of the cycler transportation vehicles as a communication relay during solar conjunctions. A cycler system is composed of one or several spacecraft placed on a trajectory that periodically encounters two space elements, in this context the Earth and Mars. This kind of transportation system could be an enabler to establish a settlement on Mars. Indeed, the vehicle is reusable for trips to and from Mars. It is maintained on its orbit mainly thanks to gravity assist maneuvers at each planet encounters. At each planet encounter, a smaller vehicle called taxi would perform a hyperbolic rendezvous with the cycler in order to transfer humans between the cycler vehicle and the surface of the planet. Finally, it offers a large living and working environment for astronauts flying to and from Mars, at reduced costs. The only study considering a cycler system

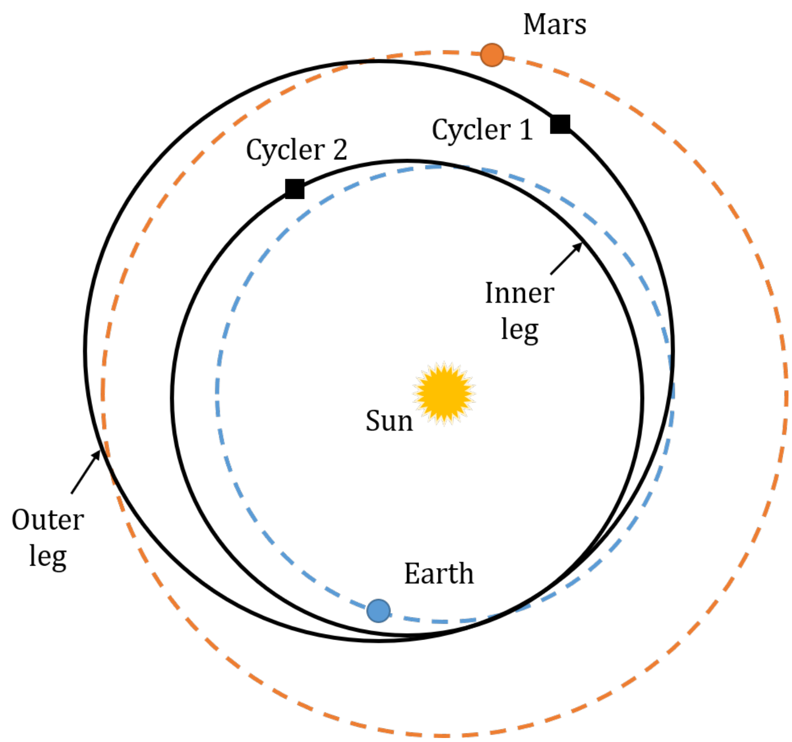


Figure 6.22: Earth-Mars S1L1 cycler trajectory

as a communication relay during solar conjunction was proposed by former astronaut Buzz Aldrin and extensively investigated by a 51-student team at Purdue University in the context of the Aldrin-Purdue project. A lot of cycler trajectories exist. In the Aldrin-Purdue study the cycler considered is the S1L1 cycler first introduced by McConaghy in 2002 [98]. The S1L1 cycler is presented in Figure 6.22 over one period. It is a two synodic period composed of two legs. The first leg, the inner leg, is short (S1). The eccentricity is 0.2554 and the semimajor axis is 1.3039. It is followed by a long leg or outer leg, L1. It crosses the Earth's orbit and then Mars' orbit 153 days later. The eccentricity is 0.1609 and the semimajor axis is 1.0483 AU. The interesting leg is the outer one, this is why two spacecraft are placed on this orbit and launched at an interval of one synodic period [49]. This architecture is **EI**.

6.4.4 Mixed architectures

The last type of architectures is the mixed architectures. They are defined as a combination of architectures from at least two of the three previous categories. Generally, these architectures fall into one of two categories:

- a combination of some satellites on heliocentric orbits with one or several relays at Lagrangian points (such as architecture **DB** by Sands et al. [99] and **DC** by Kulkarni et al. [100]) or

- a combination of a constellation around Mars with one or several relays at a Lagrangian points (such as architecture **DD** by Lorentz et al. [101], **DE** by Lida et al. [102] or **DH**).

The problem with these architectures is that they are often not completely defined, such as the SEI architectue by Hall et al.[103]. The number of satellites of the Martian constellations are not defined. Sometimes, even the orbits are nor defined. This is why most of the architectures in these category have not been implemented. To counteract this, a few architectures have been created in this category as explained in the next Chapter.

6.5 Validation

HYPOTHESIS 2: *If* a framework in a modeling and simulation environment with the required capabilities is designed *then* the communication architectures can be evaluated.

For this hypothesis, the validation criteria were the following:

1. Is the framework applicable to all the architectures?

2. Is the framework able to assess an architecture with respect to all the requirements?

3. Is the process repeatable?

The tool STK have been chosen for its capability. In terms of satellites, an important number of satellites can be implemented. We have not reached any limit during the implementation. The module Astrogator enable the computation and visualization of any kind of orbits. All the architectures have been implemented. The framework defines the environment and the way to implement the architectures. All the architectures have been implemented in this framework following the same steps. The first criteria is satisfied.

Again, STK has been chosen for its capabilities. It is the only available tool that can assess an Earth-Mars communication architectures generating some outputs on distances, trajectories and communication budget at the same time. The framework enables the implementation and the evaluation of all the architectures with respect to all the requirements. The second criterion is satisfied.

The intent in the design of the framework was to build an environment in which all the architectures can be implemented the same way based on the same assumptions. This is what we did at that step. The way to implement the architectures and to evaluate them with respect to each metrics have been extensively described in this Chapter and in the Appendices. The process have been applied the same way to all the architectures. The third criteria is satisfied.

CHAPTER 7

STEP 3 - RANKING THE ARCHITECTURES

The Chapter details the evaluation and the ranking of the architectures. As reviewed in the Chapter "Methodology Formulation", section 4.4, this last step consists of implementing the architectures described in the survey at Step 2, defining different weighting scenarios applied to the set of requirements defined at Step 1, and ranking the architectures using a TOPSIS. It concludes the methodology described in this thesis and leads to some results on the "best" architecture for a set of selected requirements, associated with a chosen weighting scenario on the requirements. In the following, I may refer to the architectures by using the term "alternatives".

7.1 Evaluation of the architectures

7.1.1 Evaluation

Most of the architectures presented in the survey performed at Step 2 are implemented. They are divided into four categories:

- the constellations around Mars (orange),
- the relays on heliocentric orbits (light blue),
- the mixed architectures that are combinations of relays and a constellation around Mars (green), and
- the heliocentric constellations or networks of relays (dark blue).

Compare to the survey performed at Step 2, I chose to add six architectures to the list of the implemented architectures. Each of these architectures is a combination of one relay satellite and one Martian constellation. The reason for adding these architectures is twofold. One the one hand, some relays are specially designed to be coupled with a constellation, such as the relay **EJ** proposed by Breidenthal et al. [48] designed to overcome the solar conjunction problem. On the other hand, from the âĂIJBackgroundâĂİ Chapter it is known that constellations perform well in terms of coverage but do not enable a continuous link availability. On the contrary, relays ensure a full link availability, but a complete coverage cannot be reached even with two relays. As a result, to have a full link availability and a complete coverage at the same time, a mixed architecture is needed. There is only one mixed architecture implemented from the survey. This is why these architectures have been added. However, the intent of this thesis is not to perform some kind of optimization or to offer new propositions of design.

To create the architectures, I picked three relays of interest.

1. The relay **EJ** by Breidenthal et al. [48], that is designed to overcome the solar conjunction problem.

2. One satellite on Gangale orbit **EK** [97], as Byford et al. have concluded that the Gangale orbit is the best location to place a relay satellite to overcome solar conjunction issues while minimizing the power required [50].

3. A relay at the Lagrangian point Sun-Mars L4 **EC** because this location is one of the most-used location for Earth-Mars communication relays.

With these three relays, a constellation has to be added. We chose to add two constellations.

1. The Draim constellation **AB** as it is the best design in terms of coverage (full coverage) with the minimum number of satellites [104].

2. The areosynchronous constellation **AO** composed by three satellites, as it is the design the most cited in mixed architectures that are not completely defined [84].

The code of these architectures starts with the letter "F". They are described in Table 7.1.

Table 7.1: Mixed architectures added for the implementation

Code	Relay	Constellation
FB	Breidenthal relay **EJ**	Draim constellation **AB**
FC	Breidenthal relay **EJ**	Three-satellites areosynchronous **AO**
FD	Gangale orbit **EK**	Draim constellation **AB**
FE	Gangale orbit **EK**	Three-satellites areosynchronous **AO**
FF	Sun-Mars Lagrangian point L4 **EC**	Draim constellation **AB**
FG	Sun-Mars Lagrangian point L4 **EC**	Three-satellites areosynchronous **AO**

In the âĂIJProblem DefinitionâĂİ Chapter, the technique selected to rank the alternatives is the TOPSIS. To be able to perform the TOPSIS, a table linking the alternatives to the metrics in a quantitative way is required. STK is used to fill this Table. The result is given Table 7.2.

Compared to the list of architectures presented in Appendix C, three groups of architectures have not been implemented. The first group is composed of the architectures that are not completely defined. They are usually mixed architectures. Indeed, some architectures such as architecture **DH** has "some satellites in low Mars orbit". I have no additional information on the number or the orbit of those satellites. Such an architecture is no implemented in order not to make any assumption on this architecture. The last two groups are the architectures with one or several satellites in orbit around the Lagrangian points L_1 and L_2 and the cycler architecture **EI**. This is because the implementation of these two groups of architectures is more complicated as the requirement for propulsive maneuvers cannot be omitted. They will be implemented in future work, they have not been implemented yet by lack of time.

7.1.2 Results by criterion

Before ranking the architectures using some weighting scenarios and the TOPSIS, they are ranked with respect to each requirement one by one. The goal is to see if the trends underlined in the âĂIJBackgroundâĂİ Chapter are found with the present methodology. The results are given on Table 7.3.

Table 7.2: Results of the implementation and evaluation of the architectures

Code	Access	Mean coverage	Delay	Number of satellites	Energy
AB	97.36%	99.14%	3.815E+08	4	1.455E+17
AC	97.36%	98.29%	3.815E+08	4	1.455E+17
AD	97.38%	33.86%	3.815E+08	6	1.455E+17
AE	97.38%	52.58%	3.815E+08	6	1.455E+17
CC	100.00%	78.73%	5.278E+08	12	1.558E+16
AF	97.38%	33.62%	3.815E+08	6	1.455E+17
AG	97.38%	31.15%	3.815E+08	6	1.455E+17
AH	97.41%	31.45%	3.815E+08	5	1.455E+17
AI	97.39%	46.97%	3.815E+08	6	1.455E+17
CB	100.00%	67.89%	6.080E+08	3	4.499E+16
AJ	97.41%	45.30%	3.815E+08	6	1.455E+17
AK	97.38%	45.31%	3.815E+08	6	1.455E+17
AL	97.40%	43.79%	3.815E+08	6	1.455E+17
AM	97.38%	100.00%	3.815E+08	6	1.455E+17
AO	97.36%	97.71%	3.815E+08	3	1.455E+17
BB	97.39%	100.00%	3.815E+08	20	1.455E+17
BC	97.40%	100.00%	3.815E+08	15	1.455E+17
DE	100.00%	97.68%	5.321E+08	7	2.387E+16
EC	100.00%	50.00%	6.119E+08	1	5.973E+16
EB	100.00%	82.28%	6.432E+08	2	7.851E+16
EF	100.00%	50.00%	5.881E+08	1	1.325E+17
EG	100.00%	94.20%	5.881E+08	2	1.544E+17
EH	100.00%	88.60%	4.223E+08	2	1.501E+17
EJ	100.00%	49.99%	4.303E+08	1	1.510E+17
EK	100.00%	50.00%	4.112E+08	1	1.403E+17
FB	100.00%	99.14%	4.303E+08	5	1.510E+17
FC	100.00%	97.71%	4.303E+08	4	1.510E+17
FF	100.00%	99.14%	6.119E+08	5	5.973E+16
FG	100.00%	97.70%	6.119E+08	4	5.973E+16
FD	100.00%	99.14%	4.112E+08	5	1.403E+17
FE	100.00%	97.71%	4.112E+08	4	1.403E+17

Table 7.3: Ranking of the architectures by requirement

Access		Coverage		Delay		Energy		Nb of satellites	
Code	%	Code	%	Code	km	Code	km²	Code	Number
CB	100.00%	BC	100.00%	BC	3.815E+08	CC	1.558E+16	EC	1
CC	100.00%	BB	100.00%	BB	3.815E+08	DE	2.387E+16	EF	1
DE	100.00%	AM	100.00%	AM	3.815E+08	CB	4.499E+16	EK	1
EB	100.00%	FB	99.14%	AB	3.815E+08	FF	5.973E+16	EJ	1
EC	100.00%	FD	99.14%	AC	3.815E+08	FG	5.973E+16	EB	2
EF	100.00%	FF	99.14%	AO	3.815E+08	EC	5.973E+16	EH	2
EG	100.00%	AB	99.14%	AE	3.815E+08	EB	7.851E+16	EG	2
EH	100.00%	AC	98.29%	AI	3.815E+08	EF	1.325E+17	CB	3
EJ	100.00%	FC	97.71%	AK	3.815E+08	FD	1.403E+17	AO	3
EK	100.00%	FE	97.71%	AJ	3.815E+08	FE	1.403E+17	FG	4
FB	100.00%	AO	97.71%	AL	3.815E+08	EK	1.403E+17	FE	4
FC	100.00%	FG	97.70%	AD	3.815E+08	BC	1.455E+17	AB	4
FD	100.00%	DE	97.68%	AF	3.815E+08	BB	1.455E+17	AC	4
FE	100.00%	EG	94.20%	AH	3.815E+08	AM	1.455E+17	FC	4
FF	100.00%	EH	88.60%	AG	3.815E+08	AB	1.455E+17	FF	5
FG	100.00%	EB	82.28%	FD	4.112E+08	AC	1.455E+17	FD	5
AJ	97.41%	CC	78.73%	FE	4.112E+08	AO	1.455E+17	AH	5
AH	97.41%	CB	67.89%	EK	4.112E+08	AE	1.455E+17	FB	5
BC	97.40%	AE	52.58%	EH	4.223E+08	AI	1.455E+17	AM	6
AL	97.40%	EC	50.00%	FB	4.303E+08	AK	1.455E+17	AE	6
BB	97.39%	EF	50.00%	FC	4.303E+08	AJ	1.455E+17	AI	6
AI	97.39%	EK	50.00%	EJ	4.303E+08	AL	1.455E+17	AK	6
AG	97.38%	EJ	49.99%	CC	5.278E+08	AD	1.455E+17	AJ	6
AD	97.38%	AI	46.97%	DE	5.321E+08	AF	1.455E+17	AL	6
AK	97.38%	AK	45.31%	EG	5.881E+08	AH	1.455E+17	AD	6
AF	97.38%	AJ	45.30%	EF	5.881E+08	AG	1.455E+17	AF	6
AM	97.38%	AL	43.79%	CB	6.080E+08	EH	1.501E+17	AG	6
AE	97.38%	AD	33.86%	FF	6.119E+08	FB	1.510E+17	DE	7
AB	97.36%	AF	33.62%	FG	6.119E+08	FC	1.510E+17	CC	12
AC	97.36%	AH	31.45%	EC	6.119E+08	EJ	1.510E+17	BC	15
AO	97.36%	AG	31.15%	EB	6.432E+08	EG	1.544E+17	BB	20

Link availability

Regarding the link availability, the architectures can be classified into two categories. One is composed by the Martian constellations that have a link availability around 97%. The second is composed by all the other architectures that all have a link availability of 100%. The constellations around Mars are the only architectures not to overcome the problem caused by solar conjunction events.

Mean coverage

In terms of coverage, the top-first architectures are the two navigation constellations, the MarsWeb constellation and the Draim constellation as well as the mixed architectures using the Draim constellation. They have a mean coverage above 99%. Second, between 80% and 99%, there are the mixed architectures, some constellations, and the relay architectures with two relays. After that, there are the heliocentric constellations, the relay architectures with only one relay. Then, the other constellations come. What is interesting is that the main asset of a constellation is to provide a full coverage of the planet. Yet, half of the constellations perform less well than only one relay. Those constellations generally perform less well in the other criteria too, they are a non-sense regarding the requirements selected.

Propagation delay

For the propagation delay, all the constellations around Mars have the same performance and come before all the other alternatives. After them, the alternatives that have the best performance in the remaining ones are those for which the relay is the closest to Mars. The architectures with a relay at a Lagrangian point L_4 or L_5 in the Sun-Mars system are the worst for the propagation delay.

Energy

In terms of energy, the trend is likely the opposite to the propagation delay. The best architectures are those for which the satellites are well-distributed in the deep-space. There are those with several satellites in heliocentric orbit, far from Mars. Then, there are the constellations, having all the same results. Finally, the architectures with a relay close to Mars are the worst.

Number of satellites

Concerning the number of elements, the best architectures are the relays, as they need only one or two satellites. The, the mixed architectures and the constellations come. The worst alternatives are the navigation constellations as they require each point of the surface to be covered by at least three satellites at the same time. They provide an additional service (navigation) that is not accounted in our requirements.

7.2 Weighting scenarios

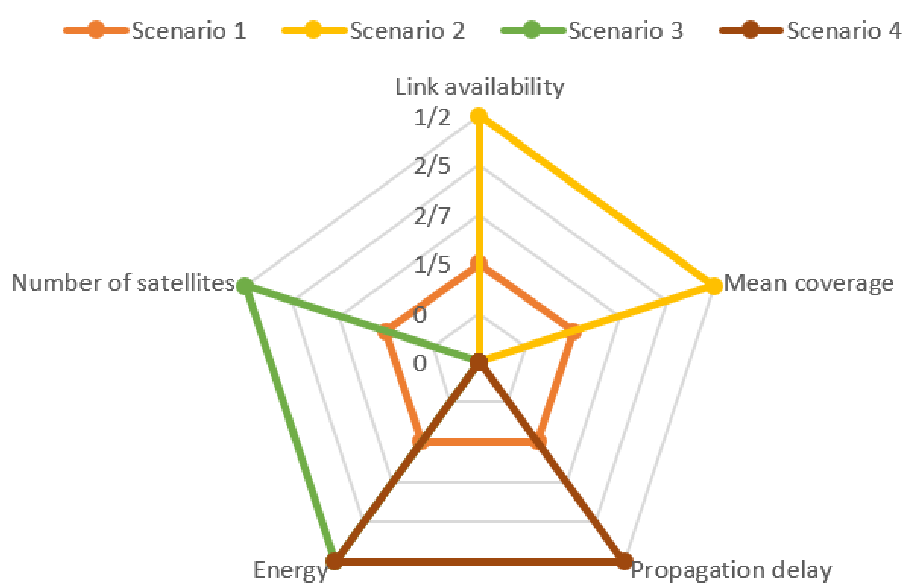


Figure 7.1: Weighting scenarios

Table 7.4: Weighting scenarios

Scenario:	**#1**	**#2**	**#3**	**#4**
Link availability	1/5	1/2	0	0
Mean coverage	1/5	1/2	0	0
Propagation delay	1/5	0	0	1/2
Energy	1/5	0	1/2	1/2
Number of satellites	1/5	0	1/2	0

The architectures have been evaluated. Before performing the TOPSIS, several weighting scenarios have to be defined. Indeed, in the TOPSIS, the importance given to each requirement can be different from one requirement to another. This was one of the reasons why this technique has been selected. Four scenarios have been established. They are defined in the Table 7.4 and represented on Figure 7.1. The choice of these four scenarios is explained in the following. Other scenarios are relevant but the objective of the thesis is to demonstrate a methodology and not to extensively compare the different architectures. Once the TOPSIS is implemented in an Excel file, the scenarios can be changed at will.

Scenario 1

The requirements in this work have been carefully selected and justified. They represent the essence of the problem of designing an Earth-Mars communication architecture. Thus, it is relevant to see what is the "best" architecture, giving the same weight to all the requirements. This is the scenario 1.

Scenario 2

The initial goal is to provide a permanent communication architecture between Earth and Mars, for all kind of missions, including manned missions. As the architecture has to served any mission, the surface covered is the first requirement. As manned mission are included, a permanent link is needed between Earth and Mars. Thus, the link availability and the coverage can be considered as the two main requirements. This is way, the second scenario focuses only on those two.

Scenario 3

As explained at Step 1, the number of elements has been added to counterbalance the data rate (translated into energy as explained at Step 2). Indeed, adding elements potentially reduces the distance between the elements and thus the power requirement. However, having more elements increases the cost of the overall architecture while decreasing the feasibility. Thus, the third scenario illustrates the trade between the energy and the number of satellites.

Scenario 4

In the previous section, when ranking the architectures for each requirement one by one, an opposite trend has been noticed between the propagation delay and the energy. Reducing the distance between elements often implies the increase of the end-to-end distance for the signal. This trade-off between the propagation delay and the energy is the purpose of the last scenario.

7.3 Ranking the alternatives

The evaluation matrix is given Table 7.2 and the scenario Table 7.4. The formulas used to perform the TOPSIS and described in the "Problem Definition" are implemented in an Excel sheet and applied to the evaluation matrix. The results architectures are ranked from the best to the worst for each scenario on Table 7.5. For each scenario, the results are discussed in the following and presented, by category, on a graph plotting the distance from the Ideal Negative point against the distance from the Ideal Positive point for each architecture. The full set of values for S_{i*}, S_{i-} and C for each alternative for each scenario is given in Appendix.

Table 7.5: Ranking of all the alternatives by scenario

Scenario 1	Scenario 2	Scenario 3	Scenario 4
CB	FB	EC	CC
EB	FD	CB	DE
FG	FF	EB	CB
EC	BC	FG	EC
FF	BB	FF	FF
EH	AM	EF	FG
AO	AB	EK	EB
EK	FC	EJ	AB
FE	FE	EH	AC
DE	FG	EG	AD
EG	DE	AO	AE
EF	AC	DE	AF
AB	AO	FE	AG
AC	EG	AB	AH
EJ	EH	AC	AI
FC	EB	FC	AJ
FD	CC	FD	AK
FB	CB	AH	AL
AM	AE	FB	AM
AH	EC	AD	AO
AE	EF	AE	BB
AI	EK	AF	BC
AK	EJ	AG	EK
AJ	AI	AI	FD
AL	AK	AJ	FE
AD	AJ	AK	EH
AF	AL	AL	EJ
AG	AD	AM	FB
CC	AF	CC	FC
BC	AH	BC	EF
BB	AG	BB	EG

7.3.1 Scenario 1

As a reminder, the scenario gives the same weight to all the requirements. The best alternative for this scenario is the architecture **CB**, an architecture with three relays in heliocentric orbit, on the same orbit as the Earth. Indeed, this solution is a good compromise between all the requirements. In particular it performs very well on three requirements: it has only three satellites, the link availability is at 100% and the distance between satellite is minimized because the relays are placed on the Earth orbit, which is better than on the Mars orbit. The coverage is at 68% which is average. The architecture do not perform well on propagation delay but this the only requirement on which the result is bad. The second best alternatives are those with a relay at the Lagrangian points L_4 and/or L_5 in the Sun-Mars system.

Looking at Figure 7.2 where all the architectures are plotted, it can be seen that relays perform better than mixed architectures that perform better than constellations architectures, on average. Among the relays, the architectures with two relays perform better than the architecture with only one relay. In terms of performance, it costs less to add a satellite and increase the coverage by 40% than not adding the satellite. On the contrary, relays performed better than a mixed architecture with the same relay and a constellation. In terms of performance, it costs more to add three or four satellites than increasing the coverage by 10%. There is a trade between the coverage and the number of elements underlying in this scenario.

The three best constellations are the three-satellites areosynchronous constellation **AO**, then the Draim constellation and **AB** then the four-satellite areosynchronous constellation **AC**. This ranking illustrates again the trade-off between the number of elements and the coverage.

Finally, the worst alternatives are those with a lot of satellites, in particular the navigation constellations **BB** and **BC**. As already underlined in the previous section, these constellations provide an additional service that is not taken into account in our set of re-

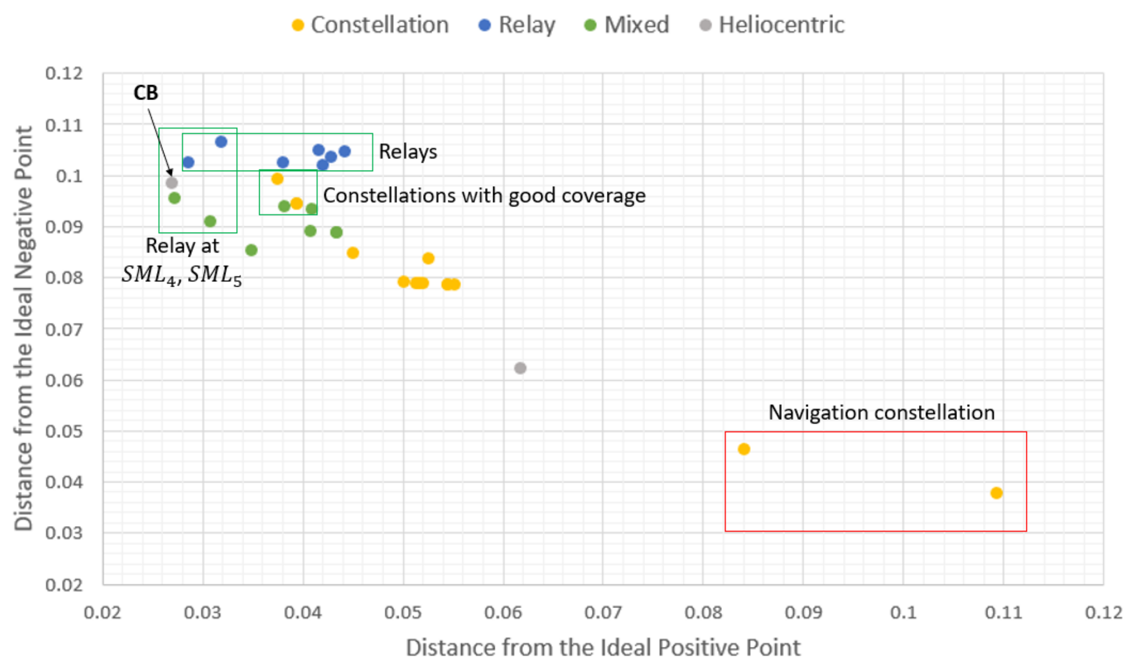


Figure 7.2: Results from Scenario 1 (Equally weighted scenario)

quirements.

7.3.2 Scenario 2

The scenario 2 only take into account the link availability and the mean coverage, with the same weight for the two requirements. It shows how the architectures perform for the two main requirements. As visualizes on Figure 7.3, the architectures are aligned on the plot. Moreover, the architectures are ranked by category in this scenario.

The best architectures for this scenario are the ones with a full link availability and a full coverage, that is to say the mixed architectures with one relay and a Draim constellation **FB**, **FD** and **FF**. After them, the architectures that perform well with a value of C above 0.95 are the constellation ensuring a full coverage, then the mixed architectures with a three-satellite areosynchronous constellation, finally the areosynchronous constellations.

After that, the classes are ranking in the order from the best to the worst: the two-relay alternatives, the heliocentric constellations, the Martian constellation **AE** that have a coverage right above 50%, the one-relay alternatives and finally the architectures with less

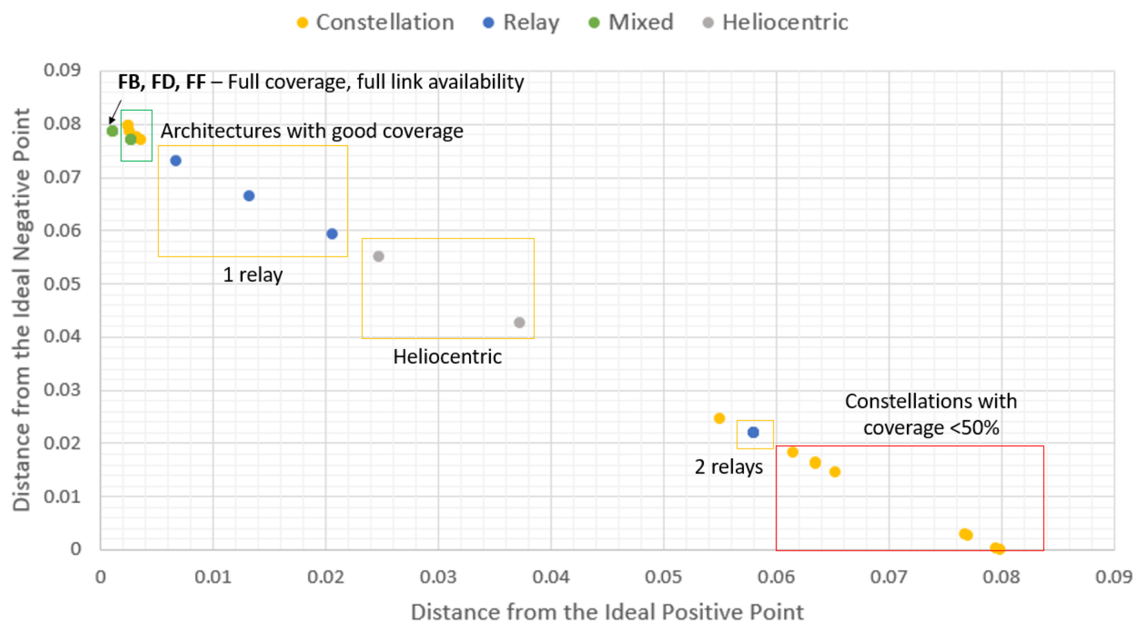


Figure 7.3: Results from Scenario 2 (Link availability and coverage)

than 50% of mean coverage. These last correspond to the constellations already emphasized at the beginning of the Chapter while ranking the architectures in by mean coverage.

7.3.3 Scenario 3

The scenario illustrates the trade-off between the energy, that is to say the distance between the elements and the number of elements. The general idea is that the more satellites they are, the closer they should be. However, as the distance considered is the largest distance between two elements, the Martian constellations are expected to be badly ranked in this scenario. Indeed, the best alternatives are those with a few number of satellites well-distributed in the deep-space. The first architecture is the relay at the Lagrangian points L_4 in the Sun-Mars system **EC**. It has only one satellite and the distance with Earth is smaller than the one for relays that are closer to Mars. The second architecture is the architecture **CB** of heliocentric relays, the same that came first in the scenario 1. The assets of this architecture is that there are only three satellites well-distributed in the deep-space. The third architecture is the combination of the two relays at the Lagrangian points L_4 and/or

L_5 in the Sun-Mars system **EB**.

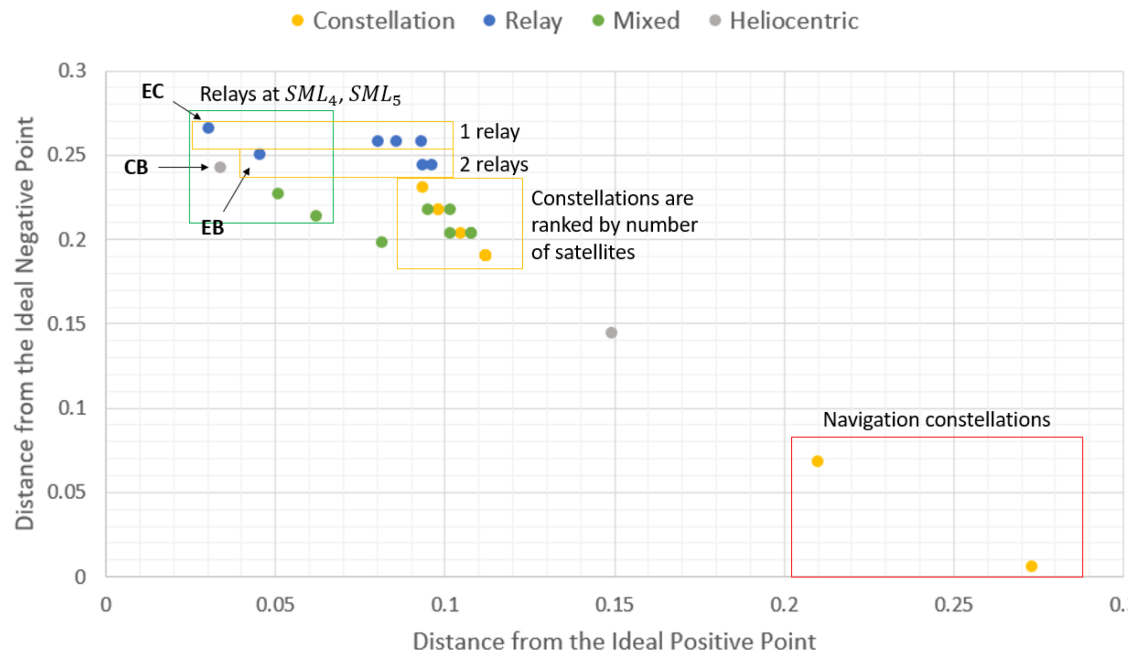


Figure 7.4: Results from Scenario 3 (Trade-off energy vs number of satellites)

All the architectures are distributed on the plot on Figure 7.4. In the first third of the ranking come the mixed architectures with a relay at the Lagrangian points L_4 in the Sun-Mars system and then all the relays. After that, there is an alternation between constellations with five or less satellites and mixed architectures. The ranking ends with constellations of more than five satellites. Again, the very last architectures are the heliocentric constellation of twelve satellites **CC** and the two navigation constellations around Mars **BB** and **BC**, as in the scenario 1.

Among the relays, the relays with only one satellites perform better than the relays with two satellites, as expected. What is interesting is that the relays that are further than Mars perform better than the relays closer to Mars. There is the idea that an architecture where the satellites are well-distributed performs better. This result goes against the conclusions drawn be Byford et al. [50]. In the paper, they review the optimal location of a relay satellite in terms of location and power requirements. This is because they assume that we can have larger antennas on Earth that will be able to transmit more power. Their reasoning is to say that they want to minimize the distance from Mars to minimize the power of the antenna on-board of the relay. This trade is explained in the "Background" Chapter. This difference in reasoning explains the difference in the results. We want to minimize the overall power required whereas they are looking for minimizing the power requirement of one element only.

7.3.4 Scenario 4

This last scenario discusses the trade-off between the energy, the maximum square of the distance between two elements and the propagation delay, the maximum end-to-end distance. This trades comes from the idea that reducing the distance between elements implies to add some elements and increase the distance travelled by the signal. On Figure 7.5 where the results are plotted for this scenario, it can be seen that there is a gap between the five first alternatives, that are themselves spaced from one to another, and the other alternatives.

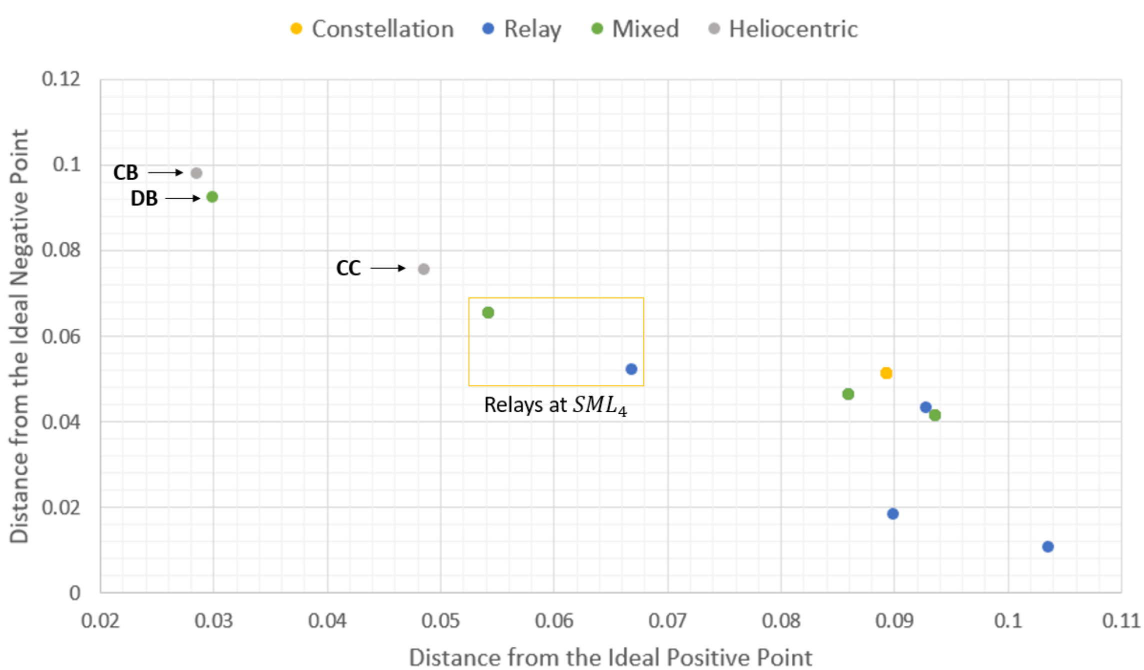


Figure 7.5: Results from Scenario 4 (Trade-off in terms of distances)

In this scenario, the architectures that perform well are those with satellites on Earth orbit. Placing satellites on Earth orbit reduces the maximum distance between two elements. Compared to a satellite on Mars orbit, for a two satellites separated by the same angle, the distance between the two will be smaller on Earth orbit as the radius of Mars orbit is bigger than the one of Earth orbit. At the same time, it does not increase to much the end-to-end distance. The first architecture is **CC**, the heliocentric constellations of twelve satellites on an 1.5 au radius orbit. Then comes the mixed architecture **DB** with two satellites at the Lagrangian points L_4 and L_5 in the Sun-Earth system. The third position is for the architecture **CB**. From those results, the reader should be surprise that there are no more proposition of design with satellites on Earth orbit, especially at the Lagrangian points L_4 and L_5.

The fourth to seventh ranks are occupied by architecture with relays at the Lagrangian points L_4 and/or L_5 in the Sun-Mars system. After that, there are all the constellation that have the same performance for this scenario as the difference of altitudes of the satellites in the constellation is negligible with respect to the distance Earth-Mars.

At the end of the ranking, there are the other option with a relay. Among these option, those that have the best results are those with a relay close to Mars. Indeed, the distance Earth-relay is important but being close to Mars decreases the end-to-end distance.

7.3.5 Comparison of the results from the different scenarios

When looking at Figure 7.5, the architecture **CB**, illustrated on Figure 7.6, is in the top-three ranking of all the scenarios except the second one. This may be surprising as the concept is original compared to classical relays and Martian constellation. There are two possible conclusions to this result. Either we did not consider enough requirement to have an accurate overview of the problem, ignoring the station-keeping problem for example. Either designers stay classical and offer solutions that looks like those that are well-known: the Lagrangian points and the constellations. This last hypothesis is close to what Sanctis writes about the design of constellations. He said that it is impossible to explore all the design space for a deep-space architecture. He also underlined that the design of constellations is far behind because of its complexity, the authors restraining themselves to circular orbits [41]. This result underlines the incompleteness of the comparisons, this design being never considered in the comparative studies found in the literature, and the lack of design space exploration. It also calls for implementing architectures such as the cyclers, that could be a good alternative.

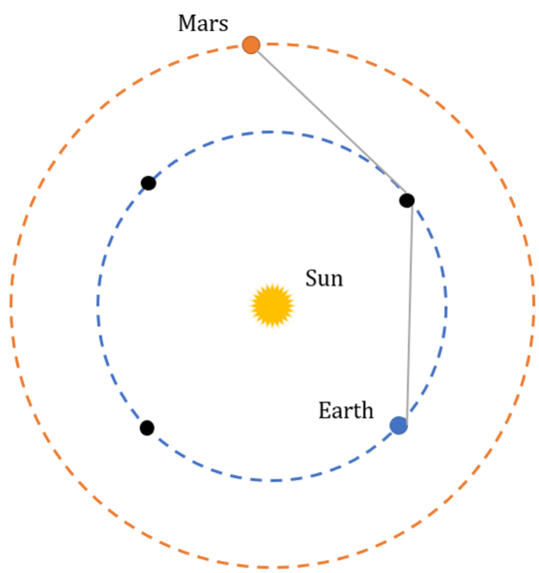


Figure 7.6: Architecture **CB**

Besides this particular design, the alternatives also performing well are those with relays at the Lagrangian points L_4 and/or L_5 in the Sun-Mars system, **FF**, **EC**, **EB** and **FG**. They have good performance in all the scenarios. Relays at Lagrangian points L_4 and L_5 are classical concepts often involved in the design of a permanent interplanetary architecture. It can be explained by the good coverage provided with only two relays and the full availability ensured.

On the other end, looking at alternatives with poor performance, there are the navigation constellations **BB** and **BC** as already discussed. It is because they provide the navigation service that is not taken into account in the set of requirements selected and that implies a higher number of satellites. There is also the architecture **CC** that only excel in the last scenario, taking the first place. This architecture is designed to enable the use of a specific communication technology, the FTL communications. These observations highlight the importance of the selection of the requirements. The requirements drive the selection of the best solution.

Finally, the constellations **AD**, **AE**, **AF**, **AG**, **AI**, **AJ**, **AK**, and **AL** have bad results in all the scenarios. The four first are compared by Bell et al. [42]. They conclude that 4retro111 (architecture **AF**) is the best of them. The difference with our analyze is that they make a trade on the altitude of the satellites. A lower altitude constellation have a higher data return and a greater precision but it has a higher gap time. This trade is not taken into here as it is too precise and too constellation-related. Our comparison is at a higher level. The four later have been designed and compared by Sanctis et al. to cover specific areas of the Martian surface [44]. Again, it cannot be compared with our study as our goal is to cover all the surface of the planet. Again, these constellations are not designed to correspond to the set of requirements selected in this thesis. It also underlines the lack of design space exploration that is mainly focused on Martian constellations. Indeed, they represent almost half of the architectures gathered from the literature.

7.4 Validation

HYPOTHESIS 3: *If* a Technique for Order Preference by Similarity to Ideal Solution is implemented *then* the comparisons performed on the communication architectures for different weighting scenarios are relevant.

For this hypothesis, the validation criteria were the following:

1. Are all the alternatives ranked?
2. Does the resulting ranking follow the trends expected from the literature?
3. Does the resulting ranking vary from one weighting scenario to another, in a cogent way?

In the work presented above, all the alternatives have been ranked in all the scenario. The first criterion is satisfied. The TOPSIS is an adequate technique to rank our alternative.

At the step we designed different weighting scenarios to illustrate some interesting trade-offs in our problem. All the results obtained have been discussed and explained by reasoning. The differences with the literature have been justified. They are explained by a difference on the assumptions made at the beginning or a difference in the level of modelization of our problem. Indeed, this study is a high-level study with the main advantage of being able to compare all the possible concepts and not only a relay of a constellation. The second criterion is validated.

Finally, the different weighting scenarios give totally different results. The difference have been explained and the results compared. The third criterion is validated.

CHAPTER 8
CONCLUSION

8.1 Summary

Because of the human imperative for exploration, it is very likely that a manned mission to Mars occurs by the end of the century. Mars is one of the two closest planets to the Earth, it is very similar to the Earth and it could be suitable to host a manned settlement. Sending humans to Mars is a technological challenge above all. Among the technologies needed, some of the most important relate to communications. Women and men on Mars need to be able to receive support from the Earth, communicate with other human beings on Earth and to send back the data collected. A reliable and continuous communication link has to be provided between the Earth and Mars to ensure a safe journey to Mars. However, the communication between the Earth and Mars is challenging because of the distance between the two planets and because of the obstruction by the Sun that occurs for about twenty-one days every 780 days. Because of the cost of communication systems and the number of exploration missions to Mars, it has been established that a permanent communication architecture between the Earth and Mars is the most profitable option. From these observations, the research goal established for this thesis is to enable reliable and continuous communications between the Earth and Mars through the design of a permanent communication architecture.

A literature review of the communication architectures between the Earth and Mars revealed that a lot of concepts have been offered by different authors over the last thirty years. However, when investigating ways to compare the variety of existing architectures, it becomes very apparent that there were no robust, traceable and rigorous approach to do so. The comparisons made in the literature were incomplete. The requirements driving the design the architectures were not defined or quantified. The assumptions on which the comparisons are based were different from one architecture to another and from one study to another. As a result, all the comparisons offered were inconsistent. This thesis addresses those gaps by developing a methodology that enables relevant and consistent comparisons of Earth-Mars communication architectures and supports gap analysis. This methodology is composed of three steps that correspond to the three main part of the thesis:

1. the definition and the mapping of the requirements against the communication system,
2. the evaluation of the architectures, and
3. the ranking of the architectures.

For each of these steps a research question was asked, and a hypothesis was formulated. All the hypotheses have been validated along the study. Here, is a summary of each step.

The first step of the methodology consists in organizing the requirements to emphasize their interactions with the different parts of the communication system (the architecture, the hardware and the software). The research question corresponding to this step was: "What process enables the mapping between the requirements and the communication system?". To address this question the hypothesis 1 was: "If a relationship matrix is developed, then the requirements are mapped appropriately against the communication system". Thus, a relationship matrix has been proposed. Beforehand, it was necessary to define a set of requirements, as a basis to assess the architectures and develop the methodology. As the requirements are often poorly defined, a review of papers about communication requirements for a manned mission to Mars has been performed. Then, a limited set of requirements has been selected to grab the essence of the problem while staying as simple and transparent as possible. Finally, the mapping took place. The hypothesis 1 was validated.

The second step of the methodology consists in evaluating the architectures. Indeed, an evaluation matrix is required to be able to rank the alternatives. The research question corresponding to this step was: "How to assess the communication architectures so that they can be consistently and rigorously compared?". To address this question the hypothesis 2 was: "If a framework is designed in a physics-based modeling and simulation environment with the required capabilities then the communication architectures can be evaluated". A modeling and simulation environment is needed. The capabilities required are the computation of trajectories for interplanetary missions, the computation of the coverage of the martian surface, the computation of the access between two elements and the computation of distances, the possibility to implement communication technologies and protocols as well as the generation of link budgets. The choice was made toward an available and user-friendly tool offering all the capabilities needed for the demonstration of the methodology and its extension: STK (Systems Tool Kit). A framework has been designed in this environment to provide a unique approach to enable the evaluation of all the architectures based on the same assumptions. It is the basis to ensure a consistent and repeatable methodology, filling one of the gaps addressed by our methodology, the inconsistencies on the assumptions made on technologies' capability (gap 2). The metrics associated with the requirements selected have been defined. A survey of the existing Earth-Mars communication architectures has been performed to populate the list of alternatives. These alternatives have been implemented in STK, following the framework designed. The hypothesis 2 was validated.

The third step of the methodology consists in ranking the alternatives. The research question corresponding to this step was: "How can communication architectures be consistently ranked?". First the architectures are evaluated to fill the evaluation matrix. To rank the alternatives, a methodology enabling a quantitative ranking of a discrete set of alternatives has been selected. This is the hypothesis 3: "If a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is implemented then the comparisons performed on the communication architectures for different weighting scenarios are relevant". To demonstrate the process, four weighting scenarios for the requirements have been carefully chosen to illustrate some trade-offs for such a system. The first scenario put the same weight on all the requirements. The second scenario focuses on the two main requirements that are the coverage and the link availability. The third scenario illustrates the trade between the energy (representing communication performance) and the number of elements. The last scenario illustrates the a trade in terms of distances, between the propagation delay and the energy. The architectures were first ranked requirement by requirement. Then, the TOPSIS was applied to the evaluation matrix for the different weighting scenarios. The results were commented. Overall, one of the best architectures for all the scenarios for the set of chosen requirements is the heliocentric concept **CB** with three satellites on Earth orbit. This result illustrates one of the gap filled by our methodology, the incompleteness of the comparisons (gap 3). Indeed, this architecture was never considered in the comparison studies found in the literature. It shows the incompleteness of the previous comparisons and emphasizes the lack of design space exploration for Earth-Mars communication architectures. The worst architectures are the navigation architectures and some martian constellations. In the first case it is because a service not taken into account in the requirements is provided. In the second case, it is because these constellations are designed to cover some selected areas of the surface of Mars, and not to provide a complete coverage as it is the intent in this thesis. This result underlines the necessity of well-defining the requirements when designing and comparing architectures, as the requirements drive the design and impact the ranking of the architecture. This finding makes the link with one of the gaps filled by our methodology, the lack of definition of the requirements (gap 1). All the architectures have been ranked for different weighting scenarios and the rankings follow expected trends. The hypothesis 3 was validated. The methodology is demonstrated.

To conclude, this thesis offers a transparent and repeatable methodology filling several gaps in the comparison of Earth-Mars communication architectures:

1. the lack of definition of the requirements,

2. the lack of a unique approach to implement and assess the architectures based on the

same assumptions, and

3. the lack of a process to rigorously compare all the architectures.

The methodology provided is demonstrated on a restricted scope, it aims at being extended as developed in the Section "Future work". It has various capabilities including:

- ranking Earth-Mars architectures based on a chosen set of requirements,
- performing gap analysis and sensitivities analysis on communication technologies and protocols, and
- performing design space exploration on architectures, not restricted to Earth-Mars architectures but also but interplanetary architectures in general, not restricted to communication architectures.

8.2 Contributions

Four contributions were made in this thesis. They are related to the methodological gaps identified in the "Background" Chapter and/or result from the shortcomings identified from the literature.

8.2.1 The methodology

Before the present research, there was no robust, consistent and rigorous means to rank and quantitatively compare the architectures. As underlined while performing the review of the requirements on Earth-Mars communication architectures, the process "Establish the need $\rightarrow$ Define the requirements $\rightarrow$ Associate some metrics $\rightarrow$ Evaluate the architectures $\rightarrow$ Rank the architectures" has never been followed consistently for Earth-Mars communication architectures. The comparisons made in the past are always incomplete or inconsistent because the requirements are not defined, the assumptions are not the same for all the architectures or the comparison is performed among a small amount of architectures. The main contribution of this thesis is the answer to the research objective: Develop a methodology that enables relevant and consistent comparisons of Earth-Mars communication architectures and supports gap analysis. The methodology not only ranks but also quantitatively compares the architectures, that is to say it can quantifies the differences between architectures for an infinite number of scenarios. This thesis offers a repeatable, traceable, transparent and rigorous methodology to carry out the process from the beginning to the end, cogently.

8.2.2 The framework in STK

The second contribution deriving from the methodological gaps highlighted in the "Background" Chapter is the design of a framework that enables the evaluation of all the architectures according to similar assumptions. The consistent and quantitative framework is a key element of the methodology developed as part of this work.

8.2.3 The requirements review

Another methodological gap is the lack of definition of the requirements. The first idea has been to look at all the papers about Earth-Mars communication architectures to see the kind of requirements and metrics that are used to design the architectures and to compared them. From this work, some conclusions have been drawn. The most cited requirements have been identified. However, the definition of those requirements was almost always incomplete. This is why a review of papers focused only on the requirements on Earth-Mars communication architectures have been done. The study of the requirements on Earth-Mars communication architectures for manned missions associated with some metrics and impacts on the design of the architectures have never been proposed before. The review has been initiated in the thesis and will be completed in future work with the impacts of the requirements on the final design of the architecture.

8.2.4 The architectures survey

The last contribution of this thesis is the survey of the Earth-Mars communication architectures at step 2. No existing paper offers an exhaustive survey of the multiple concepts proposed by different authors for this type of architectures.

8.3 Future work

The intent of this thesis was to enable reliable and continuous communications between the Earth and Mars through the design of a permanent communication architecture. The means to meet this goal was the methodology previously developed. This methodology was demonstrated on a limited scope. Indeed, only the architectures and the interactions with the hardware were considered. When assumptions on the technology were needed, the frequency considered were the X-band. This work focuses only on existing technologies and architectures. Impacting the requirements, this work is limited to the conceptual design phase and only the operation phase of the cycle of the system is considered. Consequently, this thesis can be extended in many ways, as discussed below.

8.3.1 Implementing the communication technology and performing a sensitivity analysis

The first track is to extend the methodology to take into account not only the architecture but also the technology. Indeed, one of the methodological gap is that the assumptions on the technology capabilities are inconsistent from one study to another. Implementing the technologies are easy and quite straightforward in STK but it pushes the implementation of the architecture to a lower level. Antennas, receivers and transmitters have to be defined for each elements of the architecture. A first step would be to choose an architecture, to implement two different technologies such as an X-band and a optical communication and to assess the impact of the technology on the architecture. When doing so, one must be careful not to compare two architectures with two different communication technologies.

Indeed, in such case, conclusions could not be drawn as it would be impossible to assess whether or not the difference originates from the technology or the architecture.

Another avenue for future work consist in implementing one technology and changing the capability of the technology. For example, a Ka-band is chosen and the solar exclusion angle is modified. This study is a sensitivity analysis. It correspond to the last step of the process presented in the "Methodology Formulation" Chapter. The results of such a study would enable the assessment of the impact of each technology capability on the metrics of interest. By quantifying the impact, the manufacturer and the designer would be aware of the impact of one technological development compared to one another. Eventually they would be able to identify what improvements would be needed given the requirements they set on the system and the performance desired for the system .

The last step to have a complete modeling of the communication system is to implement the protocols. This option is also possible in STK.

8.3.2 Implementing new architectures and performing optimization studies

Another avenue for future work consists in remaining at the level of the architectures but to implement more architectures. Indeed, some architectures of the survey have not been evaluated. This is either by lack of time for the halo orbits at Lagrangian points L_1 and L_2 and for the cyclers or by a lack of definition of the architecture. In the first case, the halo orbits have not been implemented because they require the implementation of the maneuvers for station-keeping in order to stay on the halo orbit for the whole duration of the synodic period. This is required to have an accurate evaluation of the coverage. Performing a deep study of cycler vehicles could be interested given that the best overall concept is a heliocentric concept, just as the cycler. It could extend the design space to new types of trajectories and offer interesting results.

Some architectures have not been implemented because the concept was not totally defined. Indeed the purpose of this thesis was limited to the comparison of existing concepts.

No optimization or modification of a design was performed. Now that the framework has been demonstrated and that the methodology is validated, another extension of this thesis could be to optimize one architecture for a selected set of requirements. STK enables design space exploration and trade studies thanks to the STK Pro and the Analyzer modules. It could be a good way to use the framework to offer new architectures designed for an established set of requirements and to perform exploration of the parts of the design space that is usually left apart, such as the heliocentric concepts and the relays on the Earth orbit.

8.3.3 Extending the set of requirements and testing other weighting scenarios

A final avenue for future work consists in modifying the set of requirements and the metrics. First, a metric corresponding to the concept that the entire surface of the Red planet is covered at all times should be introduced. By only computing the mean surface covered over one day, one does not properly assess the architecture with respect to the need of having a complete and continuous communication link between the two planets. With the link availability requirement, the continuity of the link between the Earth surface and the sphere of influence of Mars can be assess, but not with a specific location on the Mars surface. With the coverage requirement the fact that each point is reached during the day is assessed. On the contrary, the fact that any point should be reachable at any time is never assessed. To evaluate this idea, an additional metric such as the "full coverage area" could be added. This metric would compute the percentage of the surface covered at all times over one synodic period.

From the literature review, the requirements have been identified, including a quite exhaustive list made by Bhasin and Hayden [76]. Other requirements could be chosen, including other phases of the mission or other sub-systems of the satellites. Thereby, a requirement on station-keeping or on the cost to settle the architecture could be taken into account. A trade mass/size /power could also be completed, STK has the capability to assist this trade.

Other requirements could be chosen to better address some work identified in the literature. Two studies in particular could be of interest. The first one concerns the evaluation of the requirement on the coverage of polar and equatorial regions, as done by Bell [42]. The second one concerns the minimization of the distance between the relay and Mars, as proposed by Byford [50]. These two studies would be particularly interesting with the implementation of the technology.

Finally, a reflection on the way to implement and evaluate the non-functional requirements would be interesting. A requirement such as the reliability fr example, could be one of the main requirement in a manned mission. Another requirement that is very important for every space mission is the cost. The cost is difficult to implement. An easy way to take it into account is to assume that every satellite has the same cost. With this assumption, the cost is equivalent to the number of satellites. This is the requirement taken into account in this thesis. To add some accuracy to the modelling of the cost, the station-keeping requirement can be implemented. The more fuel is required, the more expensive the satellite is. The limitation is that it is still assumed that all the satellites have the same cost. However, this assumption is completely wrong. The cost of a launching a nanosatellite can be about $200 000 whereas launching an heavy satellite can reach a cost of $400 millions, and this is only for the launch. A complete model has to be developed. Other considerations, such as the technology used have to be taken into account as the choice of the technology, has to be added to the model. Indeed, it has an influence on the mass and the heavier a satellite is, the more expensive it is. An accurate model of cost is complicated and requires a certain number of assumptions.

Appendices

APPENDIX A

ARCHITECTURES AND THEIR REQUIREMENTS

Table A.1: List of the architectures with the associated requirements

Code	Ref.	Date	Type	Requirements	Description
AB	[89]	1986	Constellation	"Continuous coverage to any point on the surface" - Link availability: 100% - Surface covered: 100%	Constellation of four satellites that provides a full coverage with a minimum number of elements
AC	[88]	1989	Constellation	"Permanent relay capability" - Lifetime	Constellation of four aerosynchronous satellites
AD	[42]	2000	Constellation	"100's of Mbits per Martian day from elements at any location on the Martian surface 10m accuracy position fix to a surface anywhere on the planet in an average time of 2 hours or less" - Data volume: 100's Mbits per Martian day - Surface covered: 100% - Navigation precision: 10m	Constellation of six satellites
AE	[42]	2000	Constellation		Constellation of six satellites
AF	[42]	2000	Constellation		Constellation of six satellites
AG	[42]	2000	Constellation		Constellation of six satellites
AH	[93]	2002	Constellation	"Minimizing the transmitting time" - Propagation delay: minimized	Constellation of five satellites
AI	[44]	2007	Constellation	"An optimized Flower Constellation for the coverage of sites/regions of interest [] the north and the south poles and the equator" - Surface covered - Link availability The metrics are: - coverage percentage - mean access time - average gap time	Constellation of six satellites
AJ	[44]	2007	Constellation		Constellation of six satellites
AK	[44]	2007	Constellation		Constellation of six satellites
AL	[44]	2007	Constellation		Constellation of six satellites
AM	[45]	2009	Constellation	"high data rate", "continuous and complete coverage", "minimize the total cost" - Data rate: >500 Kbps - Link availability: 100% - Surface covered: 100% - Total cost: minimized	Constellation of six satellites
AN	[91]	2015	Constellation	"continuous high bandwidth coverage", "the system shall provide connectivity for at least 98% of the sidereal day" - Link availability: >98% - Compatibility: use the Electra protocol - Data rate: >2 Mbps - Readiness: system operational in 2035	A constellation of twenty low-orbit satellites equally distributed over four planes

Table A.2: List of the architectures with the associated requirements (continued)

Code	Ref.	Date	Type	Requirements	Description
AO	[84]	2015	Constellation	"continuous high bandwidth coverage", "the system shall provide connectivity for at least 98% of the sidereal day" - Link availability: >98% - Data rate: >2 Mbps - Readiness: system operational in 2035	Constellation of three aerosynchronous satellites
BB	[46]	2000	Navigation Constellation	- Data rate: > 100 Mbps in short range, > 1 Mbps in long range - Surface covered: 100% - Navigation precision - Redundancy - Lifetime: >10 years	A constellation of twenty satellites equally distributed over five planes
BC	[79]	2018	Navigation Constellation	"Accurate and reliable constellation" - 1. Surface covered: 100% - 1. Link availability: 100% - 2. Number of satellites: minimized - 3. Navigation	A constellation of fifteen satellites equally distributed over five planes
CB	[94]	1996	Heliocentric constellation	"Offer an alternative to the DSN" - Link availability: 100% - Cost: minimized - Data rate: 10 Mbps	Heliocentric constellation of three satellites distributed every 90 degrees from the Earth
CC	[39]	2003	Heliocentric constellation	"Faster-than-light communications" - Enable the technology	Heliocentric constellation of twelve satellites equally distributed on a circular orbit in between Earth's orbit and Mars' orbit
DB	[99]	2002	Mixed	- Data rate: 10 Mbps	Network of five satellites at Lagrangian points (Sun-Earth L3, Sun-Earth L4, Sun-Earth L5, Sun-Mars L4, Sun-Mars L5) and two on the Earth orbit equally distributed between the Lagrangian points L4 and L5

Table A.3: List of the architectures with the associated requirements (continued)

Code	Ref.	Date	Type	Requirements	Description
DC	[100]	2005	Mixed	"There is a need of an advanced, compact and well-integrated communication architecture that enables reliable, multi-nodal and high data rate capabilities to provide coverage of missions to Moon, Mars and beyond." - Surface covered - Link availability - Reliability - Data rate - Power: Minimized - Propagation delay: minimized	Three satellites at Lagrangian point (Sun-Mars L1, Sun-Mars L2 and Sun-Earth L2) and two relay on the Earth orbit located 120 degrees before and after the Earth
DD	[101]	2015	Mixed	"continuous high bandwidth coverage", "the system shall provide connectivity for at least 98% of the sidereal day" - Link availability: >98% - Data rate: >2 Mbps - Readiness: system operational in 2035	Two communication relays at the L1 Sun-Mars Lagrangian points, one relay at the L4 Sun-Earth Lagrangian Points One constellation of at least four satellites launched into a 55-degree inclination, 11706 km altitude circular orbit.
DE	[102]	2011	Mixed	- Data rate >8 Gbps	Two satellites in geostationary orbit, three aerosynchronous satellites around Mars, two relays at the Lagrangian points L4 and L5 in the Sun-Earth system
DF	[76]	2004	Mixed	"An advanced, integrated, communications infrastructure will enable the reliable, multipoint, high data rate capabilities needed on demand to provide continuous, maximum coverage of areas of concentrated activities, such as in the vicinity of in-space outposts, the Moon or Mars." - Reliability - Data rate: >100 Kbps - Link availability: 100% - Surface covered - Integrated - Cost: minimized - Lifetime - Reconfigurability - Security	One satellite at the L4 Sun-Earth Lagrangian point coupled with one to three aerosynchronous satellites around Mars, four to six satellites in High Mars orbit, some satellites in Low Mars orbit

Table A.4: List of the architectures with the associated requirements (continued)

Code	Ref.	Date	Type	Requirements	Description
DG	[103]	1992	Mixed	- Data rate: >10Mbps - Link availability: >95%	"1) low altitude, perhaps lower performance relays in highly inclined orbits for initial, globally distributed small robotic surface science packages, 2) large, higher performance, circular Mars-synchronous orbits and/or "molniya" (elliptical, non-precessing) orbits for imaging orbiter, manned vehicle and surface habitat coverage."
EB	[50] [95]	1972 2008	Relay	"Continuous communication", "cost-effective" - 1. Link availability: 100% - 2. Cost: minimized - 3. Propagation delay: minimized - Redundancy - Energy: minimized	Two satellites at the L4 and L5 Sun-Mars Lagrangian points
EC	[50]	2008	Relay	"Continuous communication", "cost-effective" - 1. Link availability: 100% - 2. Cost: minimized - 3. Propagation delay: minimized - Redundancy - Energy: minimized	One satellite at the L4 Sun-Mars Lagrangian point
ED	[47] [96]	1992	Relay	- Surface covered	Two satellites in halo orbits around Sun-Mars L1 and Sun-Mars L2
EF	[50]	2008	Relay	"Continuous communication", "cost-effective" - 1. Link availability: 100% - 2. Cost: minimized - 3. Propagation delay: minimized - Redundancy - Energy: minimized	One satellite on the same orbit as Mars but preceding Mars by 10 degrees
EG	[50]	2008	Relay	"Continuous communication", "cost-effective" - 1. Link availability: 100% - 2. Cost: minimized - 3. Propagation delay: minimized - Redundancy - Energy: minimized	Two satellites on the same orbit as Mars but preceding/following Mars by 10 degrees

Table A.5: List of the architectures with the associated requirements (continued)

Code	Ref.	Date	Type	Requirements	Description
EH	[50] [97]	2008	Relay	"Goal: Overcome the problem of interrupted communications during conjunction events while minimizing the size, mass and power requirement" - 1. Link availability: 100% - 2. Cost: minimized - 3. Propagation delay: minimized - Redundancy - Energy: minimized	Two satellites on two orbits with the same characteristics as Mars but inclined by 5 degrees respectively located 8 degrees before/after Mars
EI	[49]	2015	Relay	"continuous link" - Link availability: 100%	Two aerosynchronous satellites around Mars and two cyclers vehicles S1L1
EJ	[48]	2018	Relay	- Data rate: >3 Mbps in the forward direction, >10Mbps in the return direction - Link availability: 100%	One relay on Mars' orbit preceding Mars by 10 degrees

APPENDIX B

REQUIREMENTS REVIEW

Table B.1: Requirements review

Name	Ref.	Date	Type	Global goal / Needs and Services / Requirements / Metrics		
White	[75]	1986	This old paper is one of the first analyses of the requirements on a communication system for manned missions to Mars. It details the key communication elements that have to defined.	Drivers: - Mission objectives - Mission duration - Number of vehicles	General characteristics required: - Transparency: astronauts do not need to deal with complex embedded systems - Reliability: Little maintenance required - User responsive - Cost effective	Key communication elements: - Presence or not of a relay satellite - Frequency - Coverage - Data rate - Communication security
Bell's Mars network	[42]	2000	It describes the advantages of a permanent communication architecture. Then, it sets the performance goal and the associated metrics to evaluate different constellations around Mars.	Global goal: Design a permanent communication and navigation support infrastructure around Mars to support robotic and manned missions. These missions include elements widely spread on the surface of Mars, some of them being mobile, and manned sites require a continuous connectivity with Earth	Performance goals: - Provide global coverage - Provide high capacity, low latency communication support to the equatorial regions - Maximize coverage - Minimize the variations across the surface in terms of coverage and performance - Redundancy - Minimize orbital maintenance	Coverage metrics: - Passes/sol - Maximum Gap Time Between contacts Comm/Nav metrics: - Mbit/Sol/Watt - Mean Response Time (MRT) - Mbit/joule Performance factors

Table B.2: Requirements review (continued)

Name	Ref.	Date	Type	Global goal / Needs and Services / Requirements / Metrics		
Talbot-Stern *MCNSS (Mars Communication, Navigation and Sensing System)*	[46]	2000	It establishes a set of requirements and two associated metrics for a navigation and communication constellation around Mars. The two metrics are used to assess the architectures. The limitation of this study are the comparison of constellations only and the definition on two metrics that are not justified and does not completely translate the requirements	Global goal: Provide a robust and efficient communication and navigation system/ Provide a multiple, continuous global coverage using an integrated satellite network. The concept can be infeasible or unaffordable, but it is used for resources allocation. Needs: - Support all varieties of robotic and manned exploration mission - Science missions (robotic missions): range from the observation of the Earth to the universe and require high-bandwidth communications - Also required for robotic mission to operate autonomously - Systems that enable real-time communication or delayed-time video and control	Requirements: 1. The communication system must provide several communication links for voice, data and video at minimum specified data rates. (100Mbps in short range and 1Mbps at least in long range) 2. The navigation system must provide sufficient surface coverage for accurate navigation and precision position location methods 3. The sensing system must provide real-time weather data, as well as other scientific results of the surface when required 4. The architecture should provide sufficient redundancy and robustness so no satellite failure will result in a mission abort or catastrophic mission loss (satellite life = 10 years including transit).	Metrics: - IMHEO (Injected Mass into High Earth Orbit): give an idea of the total mass requirement - bit rate performance: total simultaneous system bit rate divided by the IMHEO
Bhasin and Hayden *The NASA vision*	[76]	2004	It develops the vision of an interplanetary communication network spreading far beyond Mars. This network is designed based on the needs expressed by the NASA Enterprises in 2010. It does not completely define the number and the orbit of the elements.	Global goal: Provide an "advanced, integrated, communications infrastructure [that] will enable the reliable, multipoint, high data rate capabilities needed on demand to provide continuous, maximum coverage of areas of concentrated activities, such as in the vicinity of in-space outposts, the Moon or Mars."	Services: - Backbone data services - Emergency - TT&C (Telemetry, Tracking and Command) - Bidirectional voice, - HDTV, - Data, - Multiples science S/C files - Remote control	Requirements: - High data rate: > 100 Mbps outside the Earth's sphere of influence by 2020 and after - See the Figure 5.3 in the body text

Table B.3: Requirements review (continued)

Name	Ref.	Date	Type	Global goal / Needs and Services / Requirements / Metrics		
Sanctis et al. *The Interplanetary Internet*	[41]	2010	It describes the concept of interplanetary internet starting with the setting of the services that has to be provides and the challenges the system faces. Then it describes the elements that could be part of the system without offering a final design.	Services (already introduced in the previous chapters): - Time insensitive transfer of large data (images and recorded videos) - Time sensitive live video streaming for the control of the rovers - Telemetry, tracking and command of landed elements and orbiters It should provide command, telemetry, data return and forwarding, emergency services, and astronaut communications.	Top-level application needs: - Type of application (video, images, files, human communications, telemetry or control data); - Number and location of data users; - Number and location of data sources; - Size and resolution of images; - Size of files; - Resolution/sampling of audio and video; - Quality of audio and video (error rate); - Updating of the scientific data (amount of data per day); - Type of positioning data (2D or 3D); - Resolution of the position data.	
Edwards et al. *The need for future Martian missions*	[77]	2001	Its starts by defining the needs by classes of missions, emphasizing the particularity of each class. However if does not give figure for all the requirements (example: "increased data return"). Then it evaluates a few relays in orbit around Mars with respect to a few metrics that correspond to common requirements.	Needs by classes of missions: - Remote sensing orbiters: continuous data rate > 100Mbps - Scout-class missions: small size (<100 kg) and very limited energy (<200 W/hrs/sol) that does not enable a direct data return - Large in-situ landers/rovers: increased data return, including data volume, link availability and support during EDL - Simple return mission: same needs as for the landers and rovers plus real-time telemetry support during launch and radio tracking - Outposts: high bandwidth data link, near continuous connectivity to establish sustained virtual presence, large mass and power budget, increased data rate - Human exploration: same needs as outposts and simple return mission, higher link availability, reliability, point-to-point communication and GPS-like navigation system		Metrics: - Passes/sol - Contact time (hrs) - Data rate for proximity link (kbps) - Data rate for Deep-space link (kbps) - Data return (Gb/sol)

Table B.4: Requirements review (continued)

Name	Ref.	Date	Type	Global goal / Needs and Services / Requirements / Metrics		
Edwards et al. *Relay communications strategies for Mars exploration*	[43]	2006	It establishes the key communication figures of merit before summarizing the current NASA's strategy in terms of communication. It reviews the current Mars orbiters and the benefit of a communication relay. The limitation is that it only considers science missions and no manned missions.	Goal: Design a communication relay to overcome significant telecommunications challenges, including the return of large data volumes from high-resolution surface instruments, highly constrained mass, power, and energy for surface spacecraft, frequent telemetry and command sessions for supporting complex surface operations, and high-risk mission events such as entry, descent, and landing for which the capture of engineering telemetry is deemed critical.	Key communication figures of merit: - Data return: high bandwidth required to transmit high-definition full-color videos - Mass and energy constraints - Contact opportunities - Critical event communication (EDL)	
Bergmann et al. *Description of Communication User and System requirements*	[78]	2009	It offers an exhaustive general description of communication requirements divided into two categories: the user requirements and the system requirements. The second category derives from the first one. However it does not propose a mapping between the two and it does not give ranges for these requirements. The description is applied to an Asteroid Simple Return mission.	Communication user requirements: *The requirements that are defined by the user.* - Communication services: data storage, virtual channels - Connectivity requirements: data quality, link availability etc. - Intra- and interoperability requirement: definition of standards, cross-linking capability - Regulation: geo return, frequency regulation, international traffic in arms regulation etc. - Security: authentication, cryptography etc. - Local mobility requirements	Communication system requirements: *Requirements derived from the user requirements* - Communication topology - Link architecture: communication technology, frequency, modulation, data rate, antenna, transmitters, receivers etc. - Storage capability: mass storage size at the end of life - Ground requirement station: availability, location, diversity of the sites etc. - Interplanetary Internet requirements: standards and protocols - Quality of service: delay, prioritization, bit error rates (BER) etc.	

APPENDIX C

ARCHITECTURES SURVEY

Table C.1: Architectures survey

NOTES:
All the references for the same concept might not have been all cited. Non-Keplerian concepts are excluded.
The Lagrangian points are referred by a code with three letters and one figure. The two first letter correspond to the two planets of the system, SE means Sun-Earth and SM means Sun-Mars. L refers to Lagrange. The figure is the number of the Lagrangian point, from 1 to 5.
Regarding the orbital elements a means semi-major axis, h means altitude, e means eccentricity, i means inclination, ω means argument of periapsis, Ω means Right Ascension of the Ascending Node (RAAN), f means true anomaly, M means mean anomaly.

Code	Name	Ref.	Year	Type	Nb	Orbital elements
AB	Four-satellite Draim constellation *Full surface coverage with the minimum number of satellites (four)*	[89]	1986	Martian constellation	4	Mars - (a, i, e, ω, Ω, M) (11104, 31.3, 0.263, -90, 0, 0) (11104, 31.3, 0.263, 90, 90, 270) (11104, 31.3, 0.263, -90, 180, 180) (11104, 31.3, 0.263, 90, 270, 90)
AC	Four-satellite aerosynchronous constellation	[88]	1989	Martian constellation	4	Mars - (a, i, e, ω, Ω, f) (20431, 0, 0, 0, 0, 0) (20431, 0, 0, 0, 0, 90) (20431, 0, 0, 0, 0, 180) (20431, 0, 0, 0, 0, 240)
AD	Multi-inclined constellation *Combination of two Walker constellations*	[42]	2000	Martian constellation	6	Mars - (h, i, e, ω, Ω, M) (800, 10, 0, 0, 0, 0) (800, 35, 0, 0, 60, 0) (400, 55, 0, 0, 120, 0) (400, 65, 0, 0, 180, 0) (400, 75, 0, 0, 240, 0) (400, 85, 0, 0, 300, 0)
AE	4inc65 *Combination of two Walker constellations*	[42]	2000	Martian constellation	6	Mars - (h, i, e, ω, Ω, M) (1100, 10, 0, 0, 0, 0) (1100, 10, 0, 0, 180, 0) (1100, 65, 0, 0, 0, 0) (1100, 65, 0, 0, 90, 90) (1100, 65, 0, 0, 180, 180) (1100, 65, 0, 0, 270, 270)
AF	4retro111 *Combination of two Walker constellations designed by the JPL to optimize the coverage of the equator and the polar regions*	[42]	2000	Martian constellation	6	Mars - (h, i, e, ω, Ω, M) (800, 172, 0, 0, 0, 0) (800, 172, 0, 0, 180, 0) (800, 111, 0, 0, 0, 0) (800, 111, 0, 0, 90, 90) (800, 111, 0, 0, 180, 180) (800, 111, 0, 0, 270, 270)
AG	4inc80 *Combination of two Walker constellation s*	[42]	2000	Martian constellation	6	Mars - (h, i, e, ω, Ω, M) (1100, 10, 0, 0, 0, 0) (1100, 10, 0, 0, 180, 0) (400, 80, 0, 0, 60, 0) (400, 80, 0, 0, 120, 0) (400, 80, 0, 0, 240, 0) (400, 80, 0, 0, 300, 0)

Table C.2: Architectures survey (continued)

Code	Name	Ref.	Year	Type	Nb	Orbital elements
AH	Mars Relay Network *The goal of this constellation is to minimize the delay from a protocol point of view*	[93]	2002	Martian constellation	5	Mars - (a, e, i, ω, Ω, f) (4084, 0.010814, 20, 249, 153, 0) (3772, 0.011474, 51, 87, 344, 0) (4052, 0.009869, -89, 292, 317, 0) (4008, 0.012156, 53, 336, 251, 0) (3890, 0.056136, 26, 46, 110, 0)
AI	FC-MARS-Single *Flower constellation optimized for the coverage of spots at polar and equatorial regions*	[44]	2007	Martian constellation	6	Mars - (a, e, i, ω, Ω, t) (4130, 0.154, 86.9, 17.7, 216.6, 272.1) (4130, 0.154, 86.9, 17.7, 276.6, 345.8) (4130, 0.154, 86.9, 17.7, 336.6, 64.9) (4130, 0.154, 86.9, 17.7, 36.6, 125.1) (4130, 0.154, 86.9, 17.7, 96.6, 172.3) (4130, 0.154, 86.9, 17.7, 156.6, 217.7)
AJ	FC-MARS-Double *Flower constellation optimized for the coverage of spots at polar and equatorial regions*	[44]	2007	Martian constellation	6	Mars - (a, e, i, ω, Ω, f) (4130, 0.015, 85.6, 303.4, 334.8, 209.8) (4130, 0.015, 85.6, 303.4, 64.8, 299.2) (4130, 0.015, 85.6, 303.4, 154.8, 31.6) (4130, 0.015, 85.6, 303.4, 244.8, 122.2) (4130, 0.015, 22, 164.5, 94.4, 299.45) (4130, 0.015, 22, 164.5, 274.4, 145.2)
AK	FC-MARS-SingleR *Flower constellation optimized for the coverage of polar and equatorial regions*	[44]	2007	Martian constellation	6	Mars - (a, e, i, ω, Ω, f) (4130, 0.07, 91, 171.1, 159.9, 188.8) (4130, 0.07, 91, 171.1, 219.9, 242.4) (4130, 0.07, 91, 171.1, 279.9, 303.2) (4130, 0.07, 91, 171.1, 339.9, 11.8) (4130, 0.07, 91, 171.1, 38.9, 78.5) (4130, 0.07, 91, 171.1, 98.9, 136.3)
AL	FC-MARS-DoubleR *Flower constellation optimized for the coverage of polar and equatorial regions*	[44]	2007	Martian constellation	6	Mars - (a, e, i, ω, Ω, f) (4130, 0.017, 88.1, 313.7, 342, 130) (4130, 0.017, 88.1, 313.7, 72, 217) (4130, 0.017, 88.1, 313.7, 162, 306) (4130, 0.017, 88.1, 313.7, 252, 39) (4130, 0.017, 49.2, 49.2, 235.1, 330.8) (4130, 0.017, 49.2, 49.2, 55.1, 330.8)
AM	MarsWeb *Constellation designed by students to maximize the global surface coverage*	[45]	2009	Martian constellation	6	Mars - (a, e, i, ω, Ω, f) (20419, 0, 37, 0, 0, 0) (20419, 0, 37, 0, 0, 120) (20419, 0, 37, 0, 0, 240) (20419, 0, 37, 0, 180, 5) (20419, 0, 37, 0, 180, 125) (20419, 0, 37, 0, 180, 245)
AO	IRIS *Three-satellite aerosynchronous constellation*	[84]	2015	Martian constellation	3	Mars - (a, e, i, ω, Ω, f) (20431, 0, 0, 0, 0, 215.7) (20431, 0, 0, 0, 0, 95.7) (20431, 0, 0, 0, 0, 335.7)

Table C.3: Architectures survey (continued)

Code	Name	Ref.	Year	Type	Nb	Orbital elements
BB	Talbot-Stern navigation constellation	[46]	2000	Martian navigation constellation	20	Mars - (a, e, i, ω, Ω, f) (17830, 0, 59.55, 0, 0, 0) (17830, 0, 59.55, 0, 0, 90) (17830, 0, 59.55, 0, 0, 180) (17830, 0, 59.55, 0, 0, 270) (17830, 0, 59.55, 0, 72, 0) (17830, 0, 59.55, 0, 72, 90) (17830, 0, 59.55, 0, 72, 180) (17830, 0, 59.55, 0, 72, 270) (17830, 0, 59.55, 0, 144, 0) (17830, 0, 59.55, 0, 144, 90) (17830, 0, 59.55, 0, 144, 180) (17830, 0, 59.55, 0, 144, 270) (17830, 0, 59.55, 0, 216, 0) (17830, 0, 59.55, 0, 216, 90) (17830, 0, 59.55, 0, 216, 180) (17830, 0, 59.55, 0, 216, 270) (17830, 0, 59.55, 0, 288, 0) (17830, 0, 59.55, 0, 288, 90) (17830, 0, 59.55, 0, 288, 180) (17830, 0, 59.55, 0, 288, 270)
BC	COMPASS	[79]	2018	Martian navigation constellation	15	Mars - (a, e, i, ω, Ω, f) (20427, 0, 45, 0, 0, 0) (20427, 0, 45, 0, 0, 120) (20427, 0, 45, 0, 0, 240) (20427, 0, 45, 0, 72, 0) (20427, 0, 45, 0, 72, 120) (20427, 0, 45, 0, 72, 240) (20427, 0, 45, 0, 144, 0) (20427, 0, 45, 0, 144, 120) (20427, 0, 45, 0, 144, 240) (20427, 0, 45, 0, 216, 0) (20427, 0, 45, 0, 216, 120) (20427, 0, 45, 0, 216, 240) (20427, 0, 45, 0, 288, 0) (20427, 0, 45, 0, 288, 120) (20427, 0, 45, 0, 288, 240)
CB	Howard network of relays *Three relays evenly distributed on Earth orbit*	[94]	1996	Heliocentric constellation	3	Heliocentric Three relays on Earth orbit distributed at +90°, +180° and +270° from Earth
CC	Faster-Than-Light heliocentric concept	[39]	2003	Heliocentric constellation	12	Heliocentric Twelve relay on a circular orbit between the Earth and Mars (radius = 1.25 au), evenly distributed (12° between each

Table C.4: Architectures survey (continued)

Code	Name	Ref.	Year	Type	Nb	Orbital elements
DB	Mars relay system *Relay on Earth orbit and at Lagrangian points*	[99]	2002	Mixed	7	Heliocentric Four relays evenly distributed on Earth orbit at +60° (SEL4), +120°, +180° and +270° (SEL5) from Earth Three relays at Lagrangian points SML1, SML2 and SEL3
DC	Moon, Mars and Beyond concept	[100]	2005	Mixed	6	Heliocentric Two relays on Earth orbit at +120° and -120° from Earth Three relays at Lagrangian points SML1, SML2, SEL2
DD	MOSAIC	[101]	2015	Mixed	>7	*Concept not enough defined to be implemented* Two relays at SML1, one relay at SEL4 Two constellation of nanosatellites in low orbit - four satellites at 1507 km altitude
DE	Mirror database of the Earth's internet	[102]	2011	Mixed	7	Two satellites in geosynchronous orbit Two relays at Lagrangian points SEL4 and SEL5 A three-satellite aerosynchronous constellation around Mars
DG	SEI Architecture	[103]	1992	Mixed		*Concept not enough defined to be implemented* "1) low altitude, perhaps lower performance relays in highly inclined orbits for initial, globally distributed small robotic surface science packages, 2) large, higher performance, circular Mars-synchronous orbits and/or “molniya” (elliptical, non-precessing) orbits for imaging orbiter, manned vehicle and surface habitat coverage."
DH	NASA architecture	[76]	2004	Mixed		One relay at the Lagrangian point SEL4 A constellation of one to three aerosynchronous satellites Four to six satellites on medium Mars orbit Some satellites on low Mars orbit
EB	Gangale Scenario 1 - Two Libration points	[50] [95]	1972 2008	Relay	2	Two relays at the Lagrangian points SML4 and SML5
EC	Gangale Scenario 1 - 1 Libration point	[50]	2008	Relay	1	One relay at the Lagrangian point SML4
ED	Halo orbits	[47] [96]	1992	Relay	2	Two satellites on halo orbit around the Lagrangian points SML1 and SML2
EF	Gangale Scenario 2 - Leading orbit	[50]	2008	Relay	1	One leading relay on Mars orbit, preceding Mars by 20°

Table C.5: Architectures survey (continued)

Code	Name	Ref.	Year	Type	Nb	Orbital elements
EG	Gangale Scenario 2 - Leading orbit and Trailing orbit	[50]	2008	Relay	2	One leading relay on Mars orbit, preceding Mars by 20° and one trailing relay following Mars by 20°
EH	Gangale Scenario 3 - Two Gangale obits	[50] [97]	2008	Relay	2	One satellite on a Gangale orbit, the same orbit as Mars but inclined by 5° preceding and following Mars by 8° respectively
EK	Gangale Scenario 3 - One Gangale obits	[50]	2008	Relay	1	One satellite on a Gangale orbit, the same orbit as Mars but inclined by 5° following Mars by 8°
EI	S1L1 Cycler	[49]	2015	Relay	4	Two cycler transportation vehicles S1L1
EJ	Relay for Mars superior conjunction	[48]	2018	Relay	1	One leading relay on Mars orbit, preceding Mars by 10°

APPENDIX D

RESULTS BY SCENARIO

Table D.1: Ranking of the architectures using the TOPSIS for the scenario 1

	Scenario 1		
	S+	S-	C
CB	0.026771758	0.098634293	0.786519405
EB	0.0285114	0.102739188	0.782771258
FG	0.027144162	0.095851018	0.779307107
EC	0.031735489	0.106816783	0.77094934
FF	0.030697196	0.091184291	0.748138976
EH	0.037899376	0.102787165	0.730611215
AO	0.03738084	0.099492823	0.726895306
EK	0.041470787	0.105205257	0.717262712
FE	0.038072044	0.094053307	0.71184906
DE	0.034730362	0.0854423	0.710996154
EG	0.041877615	0.102130888	0.709200402
EF	0.042787213	0.103830897	0.708172388
AB	0.039291866	0.094692641	0.706743214
AC	0.039297852	0.094562287	0.706426036
EJ	0.04403979	0.104892163	0.704295893
FC	0.040852695	0.093703389	0.696389091
FD	0.040681725	0.089291075	0.686998165
FB	0.043295091	0.088922419	0.672546467
AM	0.044896095	0.08498271	0.654323159
AH	0.052530393	0.084020205	0.615304556
AE	0.049986336	0.079388641	0.613632115
AI	0.051182609	0.079105452	0.607158106
AK	0.051556526	0.07903786	0.605216371
AJ	0.051558591	0.079037477	0.60520564
AL	0.051906335	0.078982492	0.60343189
AD	0.054361998	0.078774967	0.591683662
AF	0.054424812	0.078773273	0.591399439
AG	0.055079927	0.078764955	0.588479394
CC	0.061616734	0.062558229	0.503791002
BC	0.08402315	0.046667049	0.357081473
BB	0.10921151	0.037951946	0.257889745

Table D.2: Ranking of the architectures using the TOPSIS for the scenario 2

	Scenario 2		
	S+	S-	C
FB	0.000996412	0.078811009	0.987514797
FD	0.000996412	0.078811009	0.987514797
FF	0.000996412	0.078811009	0.987514797
BC	0.002363007	0.079770889	0.971229823
BB	0.002372821	0.079770885	0.971113783
AM	0.002385915	0.079770882	0.970959005
AB	0.002596369	0.078774469	0.968092145
FC	0.002653236	0.077154969	0.966754844
FE	0.002653236	0.077154969	0.966754844
FG	0.002664822	0.077143389	0.966609671
DE	0.002687995	0.077120228	0.966319325
AC	0.003111462	0.077789643	0.961539928
AO	0.003577421	0.077117644	0.955667413
EG	0.006719987	0.073090295	0.915800486
EH	0.01320825	0.066605871	0.834512362
EB	0.020530719	0.059288743	0.742785549
CC	0.024643814	0.055179269	0.691269573
CB	0.037203238	0.042635225	0.534018607
AE	0.054993481	0.024829197	0.311054421
EC	0.057930923	0.021971391	0.274978161
EF	0.057930923	0.021971391	0.274978161
EK	0.057930923	0.021971391	0.274978161
EJ	0.057942509	0.021959874	0.274833786
AI	0.06148734	0.018329363	0.229643204
AK	0.063409719	0.016406044	0.205548917
AJ	0.063420216	0.016394508	0.205407067
AL	0.065168965	0.014644972	0.183488908
AD	0.076668047	0.003139904	0.039343243
AF	0.07694607	0.002861824	0.035858909
AH	0.079458337	0.000349889	0.004384126
AG	0.079806398	1.89196E-05	0.000237012

Table D.3: Ranking of the architectures using the TOPSIS for the scenario 3

	Scenario 3		
	S+	S-	C
EC	0.030364809	0.266066652	0.897565499
CB	0.033860332	0.242775022	0.877599406
EB	0.045359604	0.249911435	0.846379772
FG	0.05080663	0.226788572	0.816975835
FF	0.062224385	0.213817018	0.774583144
EF	0.080402593	0.25842275	0.762701951
EK	0.085786441	0.258165321	0.750585835
EJ	0.093134017	0.257994937	0.734758366
EH	0.09348499	0.244424268	0.723342916
EG	0.096405871	0.244406451	0.717129151
AO	0.093383601	0.230908824	0.712038907
DE	0.081668278	0.198018139	0.708000558
FE	0.094966339	0.217464769	0.696040705
AB	0.098195346	0.217335718	0.688793412
AC	0.098195346	0.217335718	0.688793412
FC	0.101652532	0.217262469	0.681255094
FD	0.101534064	0.203900923	0.66757553
AH	0.104560444	0.203763282	0.66087448
FB	0.107813718	0.203685152	0.653887291
AD	0.112214876	0.19019166	0.62892708
AE	0.112214876	0.19019166	0.62892708
AF	0.112214876	0.19019166	0.62892708
AG	0.112214876	0.19019166	0.62892708
AI	0.112214876	0.19019166	0.62892708
AJ	0.112214876	0.19019166	0.62892708
AK	0.112214876	0.19019166	0.62892708
AL	0.112214876	0.19019166	0.62892708
AM	0.112214876	0.19019166	0.62892708
CC	0.149359498	0.144599918	0.491904358
BC	0.210044584	0.06816391	0.24501017
BB	0.273018463	0.00609706	0.021844217

Table D.4: Ranking of the architectures using the TOPSIS for the scenario 4

Scenario 4	S+	S-	C
CC	0.028518588	0.098058215	0.774693412
DE	0.029905587	0.09231506	0.755314773
CB	0.048559242	0.075531781	0.608680459
EC	0.054209236	0.065365264	0.546648858
FF	0.054209236	0.065365264	0.546648858
FG	0.054209236	0.065365264	0.546648858
EB	0.066893561	0.052165237	0.43814685
AB	0.089347825	0.0513692	0.365053196
AC	0.089347825	0.0513692	0.365053196
AD	0.089347825	0.0513692	0.365053196
AE	0.089347825	0.0513692	0.365053196
AF	0.089347825	0.0513692	0.365053196
AG	0.089347825	0.0513692	0.365053196
AH	0.089347825	0.0513692	0.365053196
AI	0.089347825	0.0513692	0.365053196
AJ	0.089347825	0.0513692	0.365053196
AK	0.089347825	0.0513692	0.365053196
AL	0.089347825	0.0513692	0.365053196
AM	0.089347825	0.0513692	0.365053196
AO	0.089347825	0.0513692	0.365053196
BB	0.089347825	0.0513692	0.365053196
BC	0.089347825	0.0513692	0.365053196
EK	0.085982101	0.046229037	0.349660685
FD	0.085982101	0.046229037	0.349660685
FE	0.085982101	0.046229037	0.349660685
EH	0.092835572	0.043146871	0.317297367
EJ	0.093619229	0.041551206	0.307398623
FB	0.093619229	0.041551206	0.307398623
FC	0.093619229	0.041551206	0.307398623
EF	0.089923124	0.018481229	0.170484196
EG	0.103592072	0.010737097	0.093913892

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