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Microcontroller-based multiple-input multiple-output transmitter systems

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2. BACKGROUND

This section provides a brief description of the background required for an effective understanding of this research work.

2.1 TYPICAL COMMUNICATION CHANNEL

A typical communication channel can be illustrated by Figure 2.1.

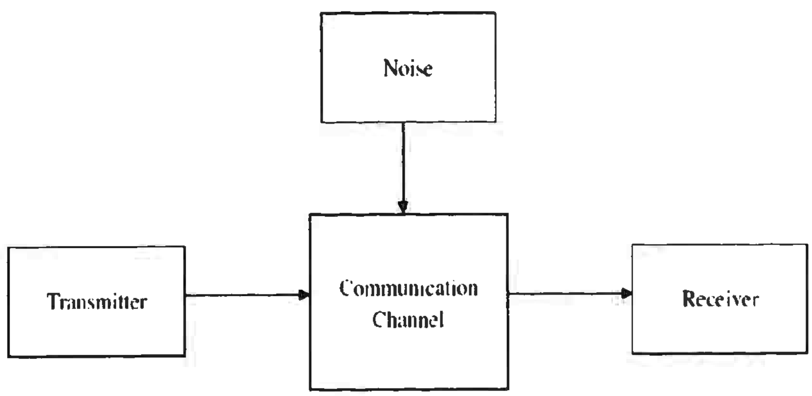


Figure 2.1 A Typical Communication System

It is clear that a typical communication system is made up of the following functional blocks:

i. Transmitter: It is an electronic device that is used to produce message signals which are transmitted using antennas

ii. Communication Channel: The channel through which the produced data is transmitted

iii. Noise: An unwanted effect that gets added to a message signal

iv. Receiver: The electronic device which is used to receive and process signals which have been captured by the receiving antenna

Noise is one of the important parameters that is always taken into consideration while designing any communication system. It often introduces error in the transmitted message signal. But certain error detection and error correction mechanisms can be used to improve the reliability of the demodulated data.

Error detection schemes like checksum algorithms, parity bits, cyclic redundancy checks (CRC's) etc. can be used. Methods such as automatic repeat request (ARQ), forward-error correction (FEC) and hybrid schemes (combination of ARQ and forward error correction) have been used for error correction [5].

2.2 ANTENNA CONFIGURATIONS

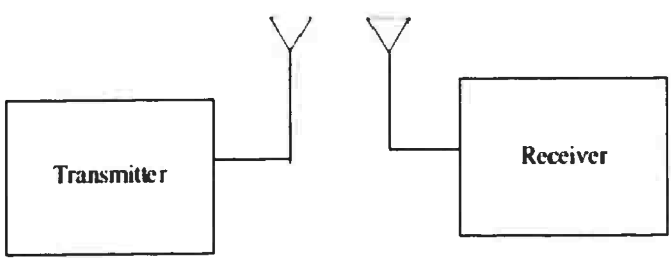
Communication systems can be implemented using a variety of antenna configurations at both the transmitter and the receiver. Some of the different configurations that can be used in a communication system are shown in Figure 2.2.

These set-ups can be explained as follows:

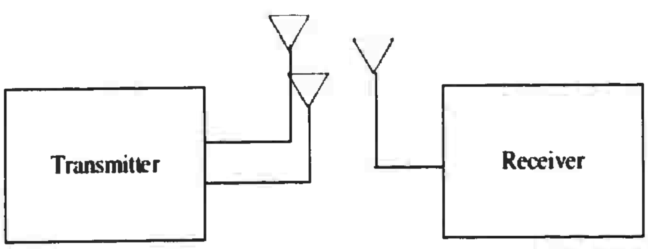
a) SISO is an acronym for Single-Input Single-Output system which simply stands for single transmitters at the transmitter and receiver ends.

b) MISO stands for the set-up that uses multiple antennas at the transmitter and only a single receiving antenna.

c) SIMO stands for the set-up that uses single antenna at the transmitting and multiple antennas at the receiving end.

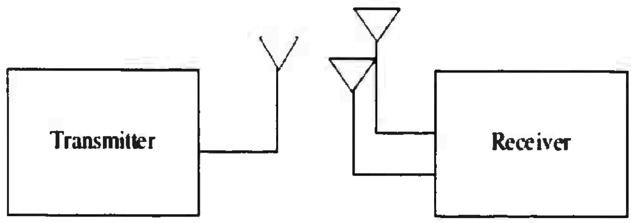


a) SISO System



b) MISO System

Figure 2.2 Different Types of Transmitter-receiver Set-ups



c) SIMO System

Figure 2.2 Different Types of Transmitter-receiver Set-ups (cont.)

Earlier designs of communication systems often focused on eliminating fading and interference, but the recent technology is more inclined towards better spectral efficiency and a low power budget [6]. This feature is exclusively provided by use of MIMO systems

2.3 MIMO SYSTEMS

This section introduces some important definitions associated with the work discussed later in the thesis. It defines some key concepts used in this work, outlines a background on how MIMO systems were introduced, and also describes its application on some of the complex communication engineering ventures. It also gives a brief description of the other approaches to communication systems, describes the challenges faced in those set-ups and finally introduces the MIMO technology.

2.3.1.Introduction. Significant improvements in capacity and bit error rates (BERs) have been a strong incentive for researchers to show more interest in multiple antenna systems, also termed multiple-input multiple-output (MIMO) systems [7]. MIMO wireless systems are those that have multiple antenna elements at both the transmitter and the receiver end [8]. MIMO systems have been known for their promising improvement in terms of performance and bandwidth efficiency [9].

The advantages of MIMO systems have been explored in many cellular technologies. Layered space-time (ST) receiver structure [7]-[9] and ST codes [13] make it possible to approach the channel capacity as revealed in [14] [15]. Commercial products working on same line are currently under development [15] [16].

A high-level block diagram for a MIMO-based communication system is illustrated in Figure 2.3.

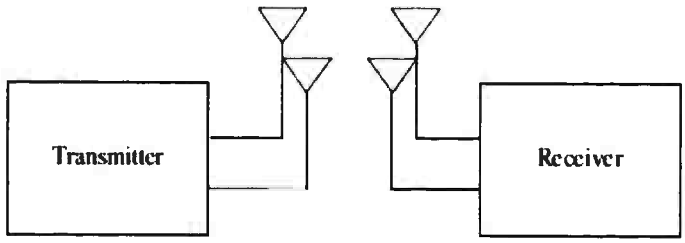


Figure 2.3 High-level Block Diagram for a Typical MIMO Communication System

It can be seen from the block diagram that the transmitter and the receiver ends are made up of multiple antennas which help MIMO systems dramatically increase the channel capacity in a fading environment [17]. These features have ensured that MIMO technology gets implemented in upcoming cellular technologies.

2.3.2.Background. The first set of ideas in the field of MIMO goes back to the work provided by A.R. Kaye and D.A George and W. van Etteh [18]. Jack Winters and Jack Salz who worked for Bell Laboratories have investigated beam forming [19]. These are considered some of the earlier works that laid foundation towards designing MIMO systems.

The concept of spatial multiplexing using MIMO systems was proposed by Arogyaswami Paulraj and Thomas Kailath [18]. Their research showed that the broadcast information capacity can be increased several-fold by this method [20]. Greg Raleigh and Gerard J. Foschini had found new approaches to the MIMO technology [10]-[14] which report that they conducted research on a Rayleigh fading environment under certain laboratory conditions[10]. These small steps in the MIMO technology ultimately helped Bell labs to demonstrate the first prototype of spatial multiplexing used to improve performance of MIMO systems [21].

2.3.3.Comparison with Related Technologies. MIMO systems have often been compared to SISO systems. It has been shown [17] that MIMO systems can support higher data rates at the same transmit power budget as SISO systems [22]. This signifies

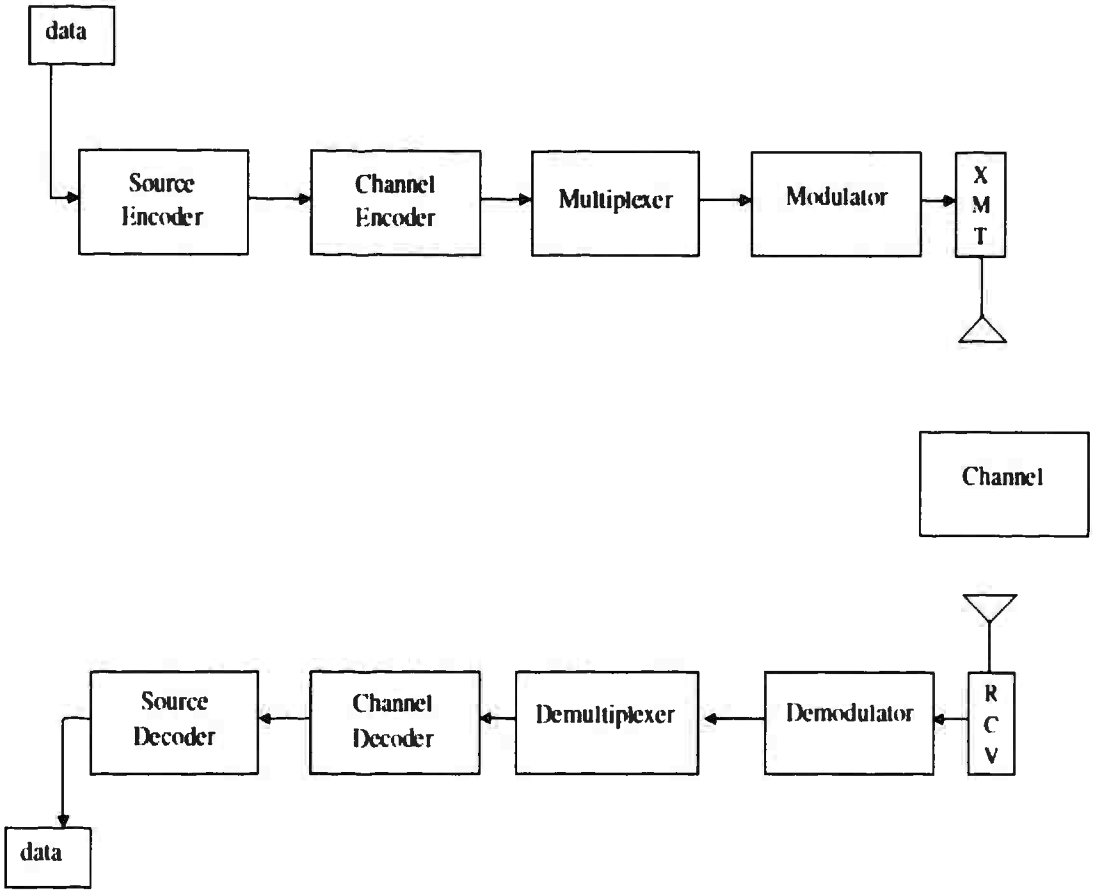


Figure 3.1 Block Diagram of a Typical Digital Communication System

4) Multiplexer: This block is used to transmit multiple data produced by same/different sources into a single line. The basic use of this is to make the system cost effective by transmitting large number of data through the same communication channel.

5) Modulator: This block is used for modulation of the channel symbol. Modulation can be defined as converting a sequence of data into suitable formats to make them compatible with specifications of a system [5]. Different types of modulation like Amplitude Modulation (AM), Frequency Modulation (FM) and Phase Modulation (PM) can be used as per the requirement of the application for the communication system.

3.2.2.Communication Channel. The channel is the medium used to transmit signals from the transmitter to the receiver. It can be a pair of wires, a coaxial cable, a band of radio frequencies, etc [33]. In wireless communication systems, band of radio frequencies are used for communication.

3.2.3.Receiver. The functionality of the different blocks of the receiver can be defined as follows:

1) Demodulator: This is the process of extracting the original signal i.e. separating the carrier signal from the original signal [14][34].

2) De-multiplexer: The multiplexer and de-multiplexer units are used to reduce the complexity and simultaneously the cost of the built system by providing an ability to send multiple signals from different sources through the channel.

3) Channel Decoder: This is used to extract the channel symbols out of the demodulated signal.

4) Source Decoder: This block is used to decode the channel symbols to extract the information signal or the message signal from it.

This summarizes the system architecture for a typical digital communication system.

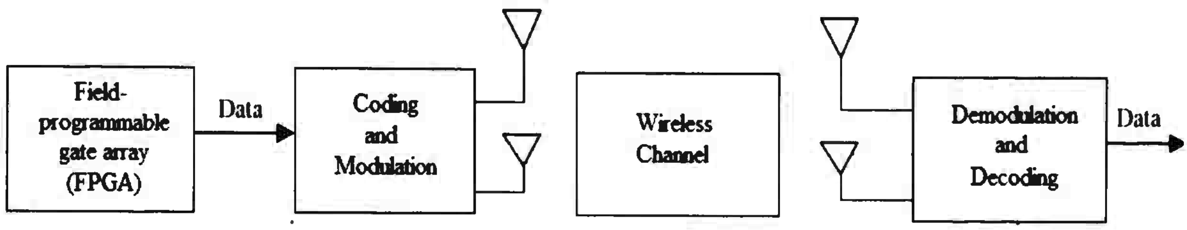


Figure 4.1 FPGA Based 2x2 MIMO System [37]
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The FPGA-based MIMO system is basically made up of three parts:

1) Transmitter End: The transmitter end is made up of the FPGA processor which is used to produce the signal which is then forwarded to the coding and modulation unit. The FPGA is used because it provides a theoretical processing capability far excess of a DSP [38].

2) Communication Channel: The wireless communication channel is used for the transmission of the signal. The various problems encountered by the signal while being transmitted through the wireless channel were explained in section 3.

3) Receiver: The receiver has a series of demodulating and decoding units. The demodulating unit is required to separate the carrier signal off from the original signal and the decoding unit is needed to extract back the original signal from the demodulated signal.

4.1.3.Features of this Approach. The various advantages in using the FPGA as a signal producing unit can be cited as follows:

1) Higher Data-rates: The use of an FPGA creates an opportunity to speed up a DSP application [37]. The capability of the FPGA to produce high data-rates can be explored and used in the field of communications.

2) Higher throughput: They have a high throughput advantage over a number of high-performance microcontroller and DSP processors for certain types of applications.

3) High flexibility and reusability: The reprogramming ability provided FPGAs has made them flexible and reusable depending on the kind of application [39]. Due to this, the FPGA hardware can be modified throughout the design cycle [40].

4.2 DSP PROCESSORS

A digital signal processor (DSP) is a device with an optimized architecture that helps it to perform many DSP operations effectively [44] [45]. The use of DSP chips has shown a significant increase in applications where their speed and numerical processing ability proved to be a blessing [46].

4.2.1.System Blocks. Digital signal processors as stated above have an incredible speed and have a very high numerical processing speed; hence they are used in some DSP application. Figure 4.2 gives the functional block diagram for a DSP based MIMO system.

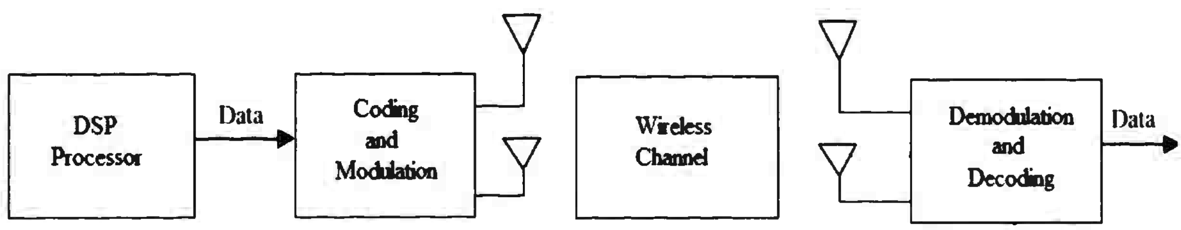


Figure 4.2 DSP Based 2x2 MIMO System

Figure 4.2 illustrated that a DSP processor is being used for producing the signal to be transmitted. The coding and the modulation block is used to provides means of mapping information into the message signal such that the receiver, using appropriate decoder and demodulator can retrieve back the sent message in a reliable manner.

The DSP-based MIMO system works on the same principle as a FPGA-based system but with some differences. The differences being the various advantages and hurdles the user faces while using either of the approaches.

4.2.2.Features of this Approach. DSP processors have been traditionally considered very effective for some DSP processes due to the following advantages:

1) Fast multiply-accumulate operation: The most important advantage cited for DSP processor is their ability to perform multiple-accumulate operation in a single instruction cycle. To help the DSP processors in performing this, it has a multiplier and an accumulator built in the arithmetic processing unit [47]. This feature has found a lot of importance in those applications which require fast processing or many multiplication operations like digital filter operations etc.

4.3 MICROCONTROLLERS

The advancements in the field of DSP world have made manufacturers add additional features into the general purpose microcontrollers which make them very attractive for many DSP applications.

A typical microcontroller cannot be used as a standalone-processor which means that it is connected to many external processes. A microcontroller analyzes the input and reacts based on the software code it is programmed with [50].

4.3.1.System Blocks. The block diagram for the Microcontroller based MIMO system is given in Figure 4.3:

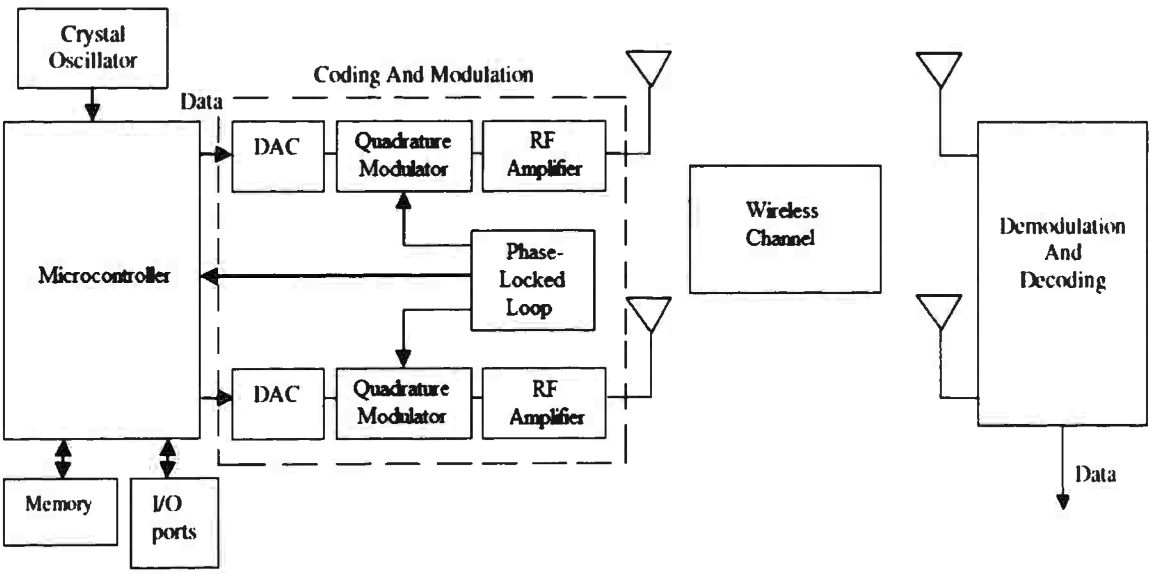
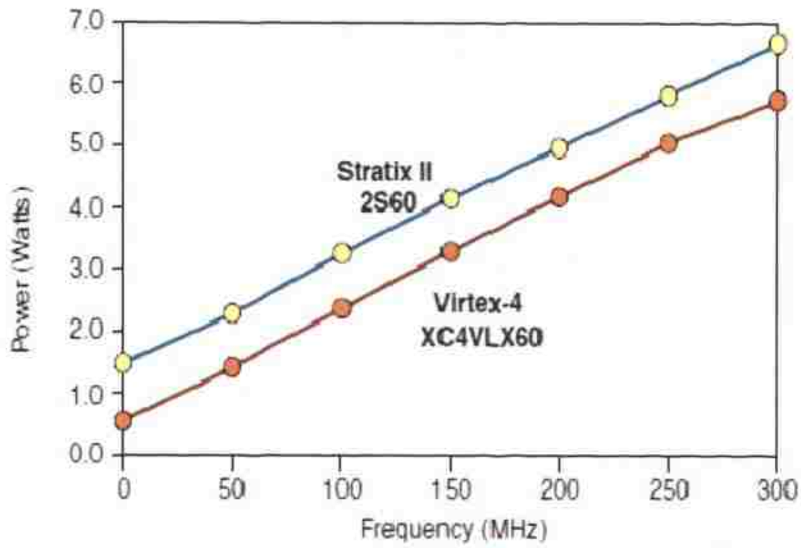


Figure 4.3 Microcontroller Based MIMO system [37]

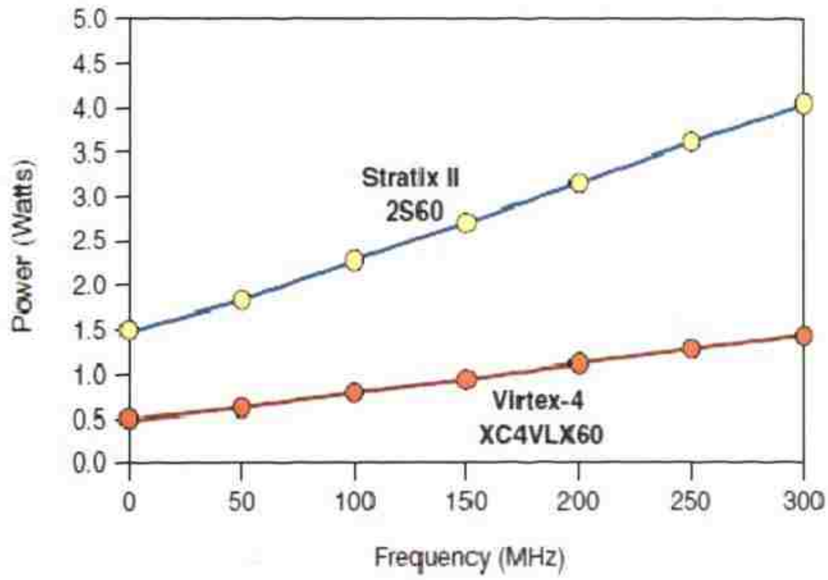
The functionality of the above figure can be explained on the same lines as FPGA and DSP, but it can be seen that the microcontroller itself is connected to a lot of external chips. This helps it to undertake multiple functions at the same time, which is one of the features that has helped it succeed in the field of communications.

4.3.2.Features of this Approach. The various advantages of a typical microcontroller can be given as follows:

1) Lower power consumption and low cost: It is found that DSP processors execute multiple instructions within a single cock cycle and hence they consume more power. The FPGA has flexibility, but this comes at the cost of higher power

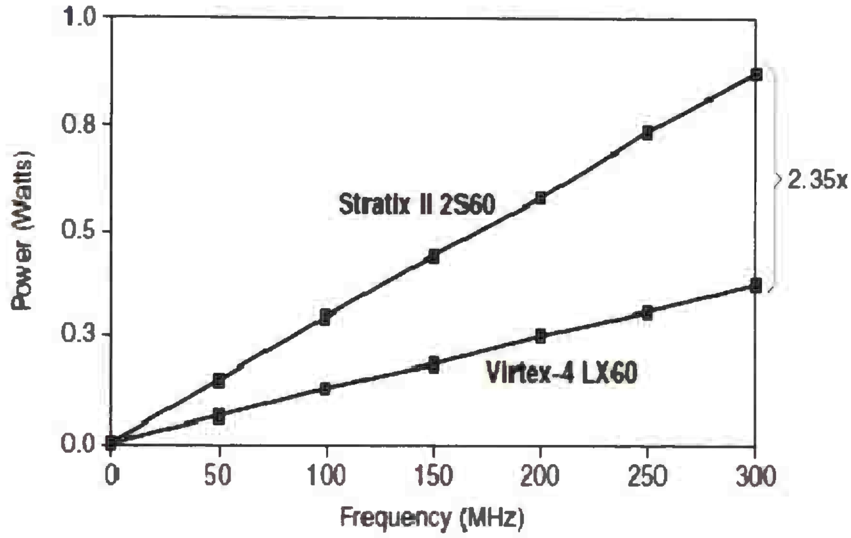


a) Dynamic Power: Fabric Test with 25,000 LUT/ALUTs and 21,000 FFs (High Toggle Rate). All measurements were taken at Tj = 85°C.

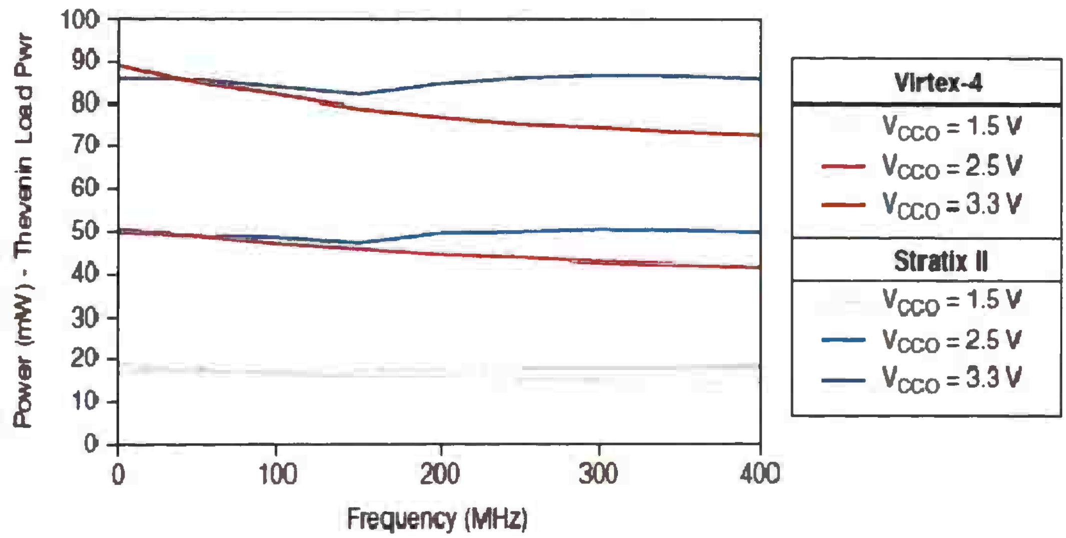


b) Dynamic Power :Memory using FIFO/Block RAM test with 252 M4K in Stratix II and 63 Block RAM in Virtex-4FPGAs (same total storage).
All measurements were taken at Tj = 85° C.

Figure 5.1 Dynamic Power Consumption of Virtex-4 and Stratix-II for Different Tests[57]



c) Dynamic Power: DSP test: 64-tap FIR filter



d) Dynamic Power at all three VCCIO voltages

Figure 5.1 Dynamic Power Consumption of Virtex-4 and Stratix-II for Different Tests[57] (cont.)

It can be inferred from Figure 5.1 that the considered FPGAs consume large dynamic power for most of the above tests. Specifically for the fabric test, it can be seen that the both the FPGAs consume 6-7 Watts of power, which is considered pretty high for most DSP applications. Figure 5.2 gives a brief summary about the total power dissipation of Stratix-II and Virtex-4.

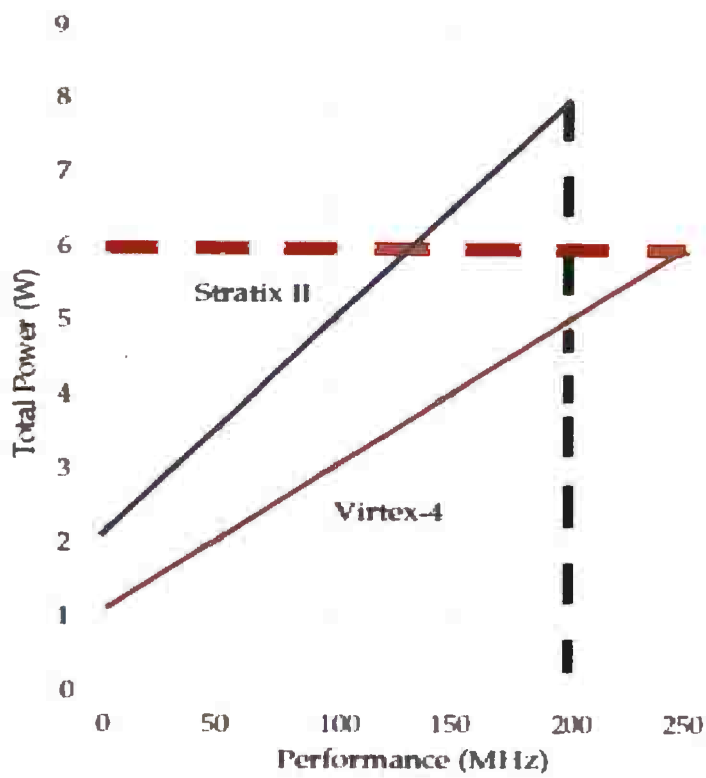


Figure 5.2 Total Power Consumption for Virtex-4 and Stratix-II [57]

In Figure 5.2 total power consumption for Stratix-II is found to be ≈8W and that for Virtex-4 is found to be approximately 5W. Thus from these values it is clear that dynamic power consumption plays an important role in deciding the total power consumption of the system.

Recent developments in the field of chip design have come-up with ideas that can reduce the total dynamic power consumption. But at the present time, it remains one of the major parameters that are to be considered before opting for an FPGA design.

7. HIGH-LEVEL BLOCK DIAGRAM DESCRIPTION

The high-level block diagram of the considered approach can be illustrated by Figure 7.1:

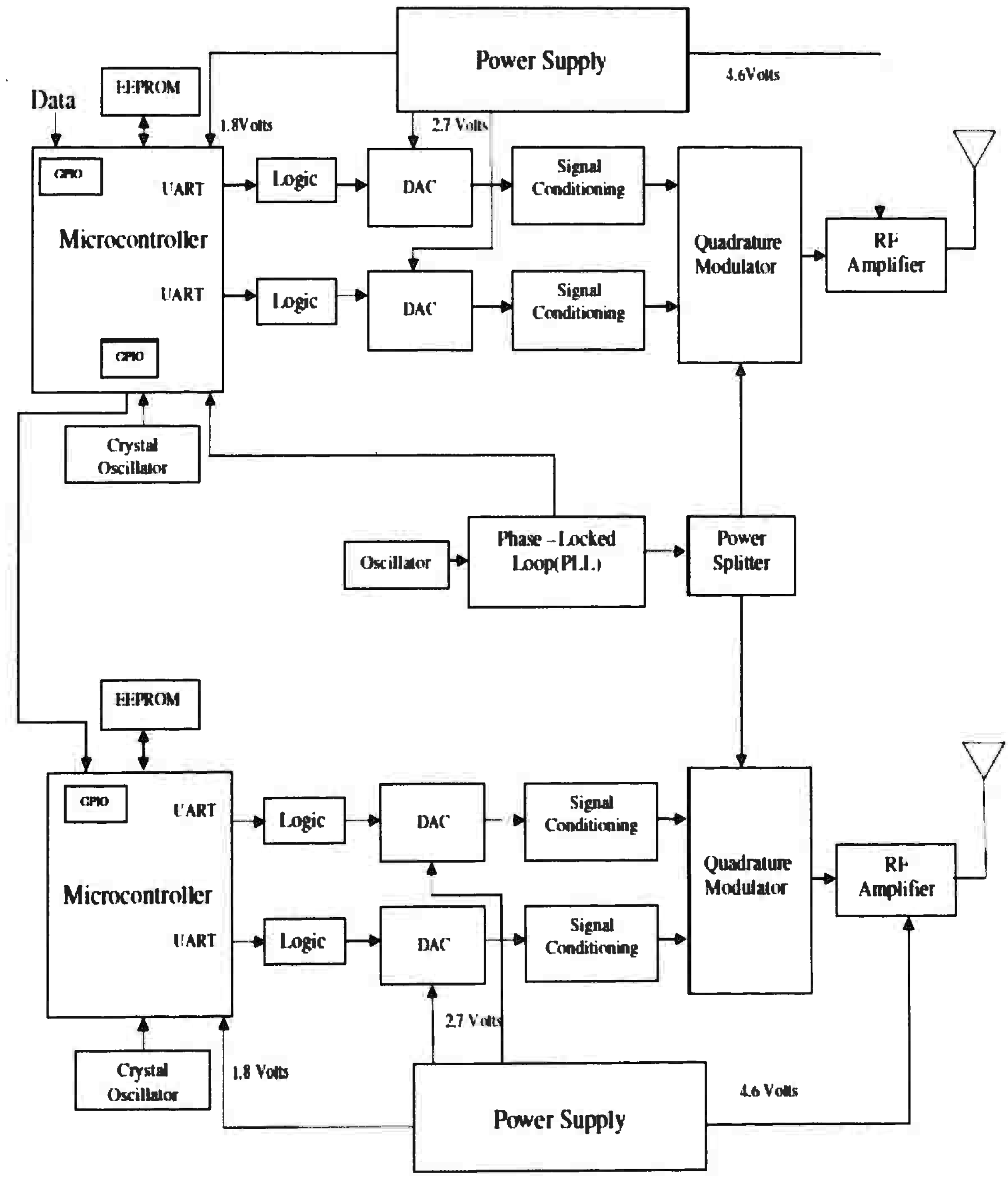


Figure 7.1 High-level Block Diagram for a Microcontroller Based MIMO Transmitter [37]
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The various parts of the above diagram as be explained as below:

7.1. MICROCONTROLLER

Microcontrollers can be considered as a small computer designed on a single integrated circuit along with support devices like processor, memory and peripherals [58]. It may also include other support devices like A/D converters and serial I/O ports. In practical systems, the microcontroller is found to be a part of the system used to undertake specific functions related to the application.

Figure 7.2 illustrates the internal block diagram of a typical microcontroller and the blocks are explained in the corresponding sub-topics.

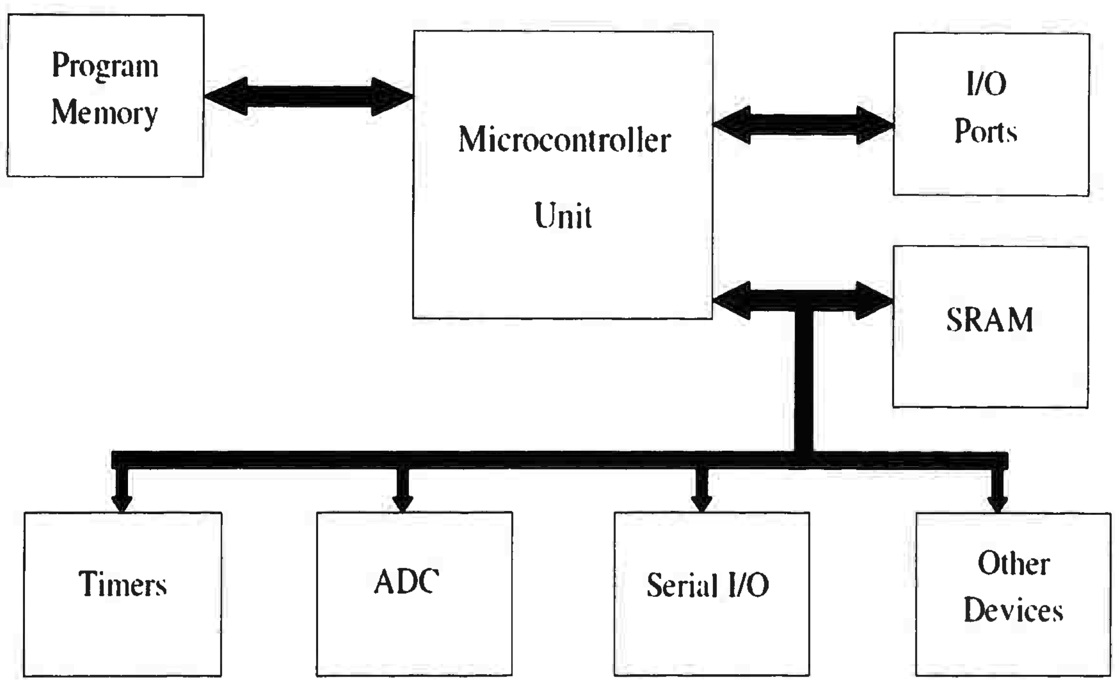

Figure 7.2 Block-diagram –microcontroller

7.1.1.Microprocessor. The Microprocessor Unit (MPU) unit is considered to be its brain of the microcontroller. Every MPU has three units as illustrated by Figure 7.3 and described as follows:

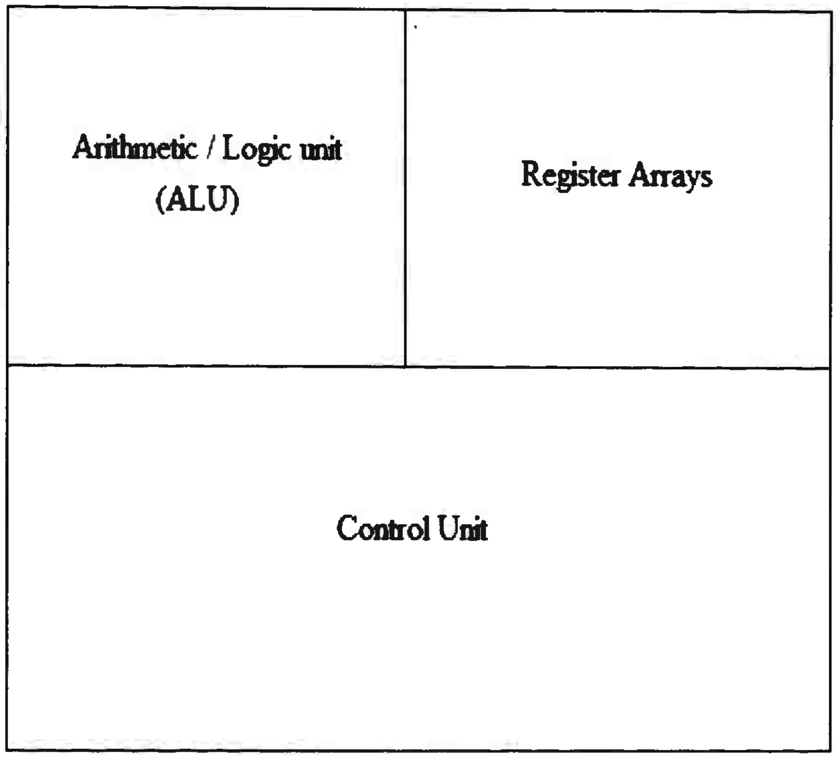

Figure 7.3 Block-diagram –microprocessor (MPU) Unit

Control Unit: This the main part of the MPU unit which is used for processing the instructions provided to it and enabling the connected devices to work according to the application [59].

Arithmetic / Logic Unit (ALU): This unit of the microcontroller is used to perform arithmetic and logic operation like addition, multiplication, performing AND / OR/ XOR operations etc

Register Arrays: The various registers are either used for storing data temporarily or permanently.

7.1.2.Memory. This is one of the integral parts of the microcontroller. It is basically used to store both instructions and data [52]. Modern day microcontroller comes with very large internal integrated memories which help it to perform faster and hold more data. An external memory can also be interfaced with a microcontroller to improve its performance and also ability to process long instructions and also long-stream of data.

7.1.3.Input/output (I/O) Devices. External input/ output peripheral devices can be connected to a microcontroller. Input devices include switches and keyboards. Output devices could be LCD devices, light-emitting diodes (LED's) etc.

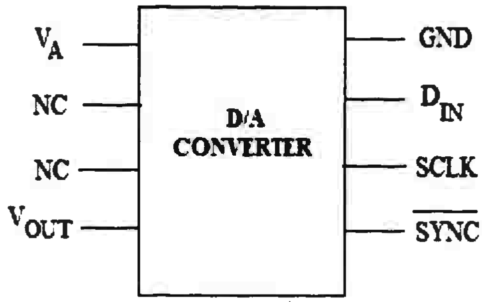

Figure 7.4 Pin Diagram of D/A Converter

The digital data from the microcontroller (UART) comes toD_{IN}. The digital signal is then converted into an analog signal and sent to V_{OUT} pin. V_A(2.7 Volts) is the voltage required by the D/A converter to function. The other pins of the D/A can be defined as follows:

1) SCLK: This is a serial clock input. Data is clocked to an internal shift register on the falling edge of this pin.

2) $\overline{SYNC}$: This is a frame synchronization input for the data input. When this pin goes low it enables the input shift register and the data is transferred at every falling edge of SCLK.

7.3. LOGIC BLOCK

The D/A requires SCLK, $\overline{SYNC}$ along with the digital data. The data from the DAC is at a very high frequency ($\approx$ 10MHz), so a perfect precision is required while extraction of SCLK and $\overline{SYNC}$ signals.

These two signals need to be extracted by a logic block and the high-level block diagram for the logic block used to generate the desired signals using the microcontroller generated data bits is shown in Figure 7.5.

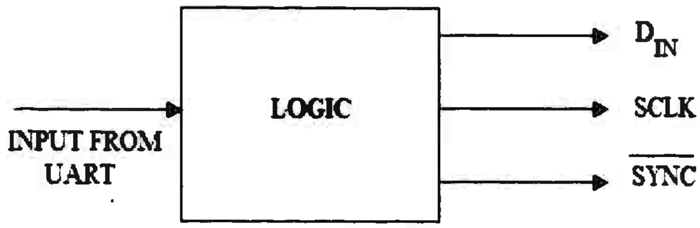

Figure 7.5 Logic Block Diagram

7.4. QUADRATURE MODULATOR

The quadrature modulator is used to modulate message signals (analog or digital) with carrier signals used for radio communications [29]. A typical quadrature modulator is basically made of a mixer, a summation block and a phase shifter [61]. In its application with MIMO system it is used on analog signals. It basically transmits two analog signals by modulating the amplitude of two carrier signals which are out of phase by Amplitude Modulation (AM) [37]. Figure 7.6 illustrates the block diagram of the quadrature modulator.

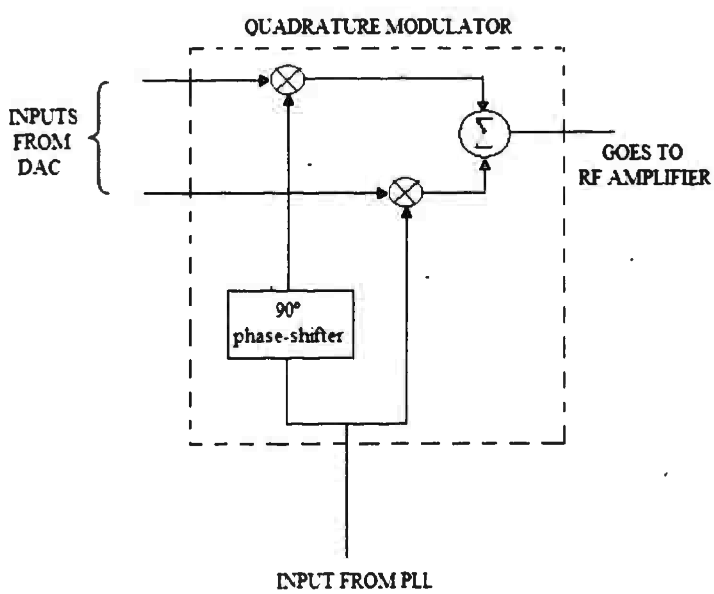

Figure 7.6 Block Diagram of Quadrature Modulator [37]
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The analog signals from the DAC are used as the message signal which is then modulated by the phase-shifted carrier signals provided by the Phase-locked Loop (PLL). One of the signals is used directly and the other is phase shifted by 90°.