Permission to Borrow

In presenting this dissertation as a partial fulfillment of the requirements for an advanced degree from Georgia State University, I agree that the Library of the University shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to quote from, or to publish this dissertation may be granted by the author or, in his/her absence, the professor under whose direction it was written or, in his absence, by the Dean of the Robinson College of Business. Such quoting, copying, or publishing must be solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from or publication of this dissertation which involves potential gain will not be allowed without written permission of the author.

_____

signature of author

Notice to Borrowers

All dissertations deposited in the Georgia State University Library must be used only in accordance with the stipulations prescribed by the author in the preceding statement.

The author of this dissertation is:

Sweta Sneha
3642 Summit Oaks Drive
Roswell GA 30075

The director of this dissertation is:

Dr. Upkar Varshney
Computer Information Systems Department
Robinson College of Business Administration
P.O. Box 4015
Atlanta GA 30303-4015
Telephone: 404-651-3880 ext. 9139
Georgia State University

Users of this dissertation not regularly enrolled as students at Georgia State University are required to attest acceptance of the preceding stipulations by signing below. Libraries borrowing this dissertation for the use of their patrons are required to see that each user records here the information requested.

Name of User	**Address**	**Date**

PATIENT MONITORING VIA MOBILE AD HOC NETWORK - MAXIMIZING RELIABILITY WHILE MINIMIZING POWER USAGE AND DELAYS

BY

SWETA SNEHA

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree

of

Doctor of Philosophy

in the Robinson College of Business

of

Georgia State University

GEORGIA STATE UNIVERSITY

ROBINSON COLLEGE OF BUSINESS

2008

ACCEPTANCE

This dissertation was prepared under the direction of Sweta Sneha's Dissertation Committee. It has been approved and accepted by all members of that committee, and it has been accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Robinson College of Business of Georgia State University.

_____
Dean
Robinson College of Business

Dissertation Committee:

_____
Chair: Dr. Upkar Varshney

_____
Dr. Peter Meso

_____
Dr. Yi Pan

_____
Dr. Anu Bourgeois

ABSTRACT

PATIENT MONITORING VIA MOBILE AD HOC NETWORK - MAXIMIZING RELIABILITY WHILE MINIMIZING POWER USAGE AND DELAYS

BY

SWETA SNEHA

May 22nd, 2008

Committee Chair: Dr. Upkar Varshney
Major Department: Computer Information Systems

Comprehensive monitoring of patients based on wireless and mobile technologies has been proposed for early detection of anomalies, provision of prompt medical attention, and corresponding reduction in healthcare expenses associated with unnecessary hospitalizations and treatment. However the quality and reliability of patient monitoring applications have not been satisfactory, primarily due to their sole dependence on infrastructure-oriented wireless networks such as wide-area cellular networks and wireless LANs with unpredictable and spotty coverage. The current research is exploratory in nature and seeks to investigate the feasibility of leveraging mobile ad hoc network for extending the coverage of infrastructure oriented networks when the coverage from the latter is limited/non-existent.

Although exciting, there are several challenges associated with leveraging mobile ad hoc network in the context of patient monitoring. The current research focuses on power management of the low-powered monitoring devices with the goal to maximize reliability and minimize delays. The PRD protocols leveraging variable-rate transmit power and the PM-PRD

scheme are designed to achieve the aforementioned objective. The PRD protocols manage power transmitted by the source and intermediate routing devices in end to end signal transmission with the obejective to maximize end to end reliability. The PM-PRD scheme operationalizes an appropriate PRD protocol in end to end signal transmission for diverse patient monitoring scenarios with the objective to maximize reliability, optimize power usage, and minimize delays in end to end signal transmission.

Analytical modeling technique is utilized for modeling diverse monitoring scenarios in terms of the independent variables and assessing the performance of the research artifacts in terms of the dependent variables. The evaluation criterion of the research artifacts is maximization of reliability and minimization of power usage and delays for diverse monitoring scenarios. The performance evaluation of the PRD protocols is based on maximization of end to end reliability in signal transmission. The utility of the PM-PRD scheme is associated with operationalizing an appropriate protocol for a given monitoring scenario. Appropriateness of a protocol for a given scenario is based on the performance of the PRD protocols with respect to the dependent variables (i.e., end to end reliability, end to end power usage, and end to end delays). Hence the performance evaluation of the PRD protocols in terms of the dependent variables is utilized to (a) discover the best protocol and (b) validate the accuracy and utility of the PM-PRD scheme in allocating the best protocol for diverse monitoring scenarios.

The results validate the effectiveness of the research artifacts in maximizing reliability while minimizing power usage and delays in end to end signal transmission via a multi-hop mobile ad hoc network. Consequently the research establishes the feasibility of multi-hop mobile ad hoc network in supplementing the spotty network coverage of

infrastructure oriented networks thereby enhancing the quality and dependability of the process of signal transmission associated with patient monitoring applications.

ACKNOWLEDGEMENTS

There are many people whose relentless support and guidance not only helped me mature professionally as a scholar but also helped me get through tough times on the personal front. I would not have reached so far in my career as a researcher if it wasn't for their support. I would like to thank all of them.

First, I would like to thank my advisor, Dr. Upkar Varshney, who initiated my career as a researcher and motivated me to apply for the Ph.D. program. Since then I have known what I want to do for the rest of my life. Dr. Varshney has been a constant source of encouragement and his thoughtful consideration has uplifted me on numerous occasions. My dissertation has greatly benefited from his wisdom and superior knowledge of the subject matter. I have also gained personally from his mentorship and guidance. Thanks for everything!

I would also like to thank my committee members: Dr. Peter Meso, Dr. Yi Pan, and Dr. Anu Bourgeois in shaping and helping improve the dissertation. My dissertation benefited greatly from the keen acumen and mentorship of my committee members. Without your relentless support and suggestions the proposed dissertation would not exist. I thank you for your time and patience in dealing with me, my requests for feedback, and defense scheduling.

I feel extremely privileged to have been able to learn and work with some of the most acclaimed researchers at GSU. I would like to thank Dr. Veda Storey, Dr. Bala Ramesh, and Dr. Vijay Vaishnavi in introducing me to design research and giving me the tools to grow and

conduct rigorous research utilizing design research methodology. Dr. Storey continues to inspire me with the grace she manages her personal and professional lives.

Dr. Detmar Straub has been my mentor and support during my entire career at GSU. I have been very fortunate to be able to work with and learn from him. He has been instrumental in shaping my research career and in giving me wonderful opportunities in expanding my horizon from the very beginning of the Ph.D. program. I cannot thank him enough for his mentorship and kindness.

Dr. Daniel Robey has been a source of excellent advice and support during my entire stay at GSU. I still remember meeting him for the very first time at GSU on a Friday afternoon when he gave me a short tour of the department. His seminar on qualitative research methods encouraged me to explore the realm of interpretive research. Dr. Mark Keil gave me an opportunity to conduct research in the domain of project management. I have learnt a lot from him both professionally and personally and admire his courage and optimism in the face of difficulty.

I thank my fellow PhD students, especially, Alina Dulipovici, Robert Sainsbury, Mike Cuellar, Hirotoshi Takeda, Yi Ding, Jonathan Kim, Steve Du, Nannet Napier, Yide Shen, Jijie Wang, Jack Zheng, Chongwoo Park, Stacie Petter, and Adriane B. Davis, with whom I have shared numerous laughs and good times. Their support and friendship made the journey at GSU a memorable one. I also thank the GSU staff who helped me on numerous occasions and helped me settle in the department especially Elizabeth Carpenter, Jessica Burgess, Mohammed, Libby Crawley, and Carol Patterson. Without their support my time at GSU would not have been as smooth.

I would like to thank all those who have been with me all along the journey. I could not have reached so far if it wasn't for their relentless love and support:

- First and foremost are my dear husband (Chetan Rischie) and my adorable son (Ishaan Rischie) who have been a constant source of unsurpassed love, support, and encouragement. My husband Chetan has been my source of strength, perseverance, and joy. His small thoughtful considerations reflecting his love and care meant the whole world to me and helped me survive the rigors of the PhD program. He believed in me even when I didn't and supported me in numerous ways from letting me sleep in for an hour in the morning because I stayed up all night, cooking/ordering in meals, helping with the laundry/dishes, dealing with busy days/nights and my highs/lows, and the list goes on and on. I am extremely proud of my son Ishaan who has been my source of inspiration and true bliss even in difficult times. His mere presence enriches my life and brings me smile and true happiness. His caring thoughts and actions at such a young age continues to overwhelm and surprise me. I am truly blessed to have both of you in my life. Even though I don't say it often, I love you both today and always and I hope I can bring you as much happiness as you have brought me.

- Second, are my mom (Mrs. Mukti Shrivastava) and dad (Dr. C.P. Shrivastava) whose unconditional love strengthens me even today and gives me the courage to face the toughest times. They have been phenomenal parents and I hope I am being as good a parent as they are. I love them very much and am completely awed by what they have done for me. To my grandfather (Mr. T.N. Verma) and grandmother (Mrs. Sneh Lata Verma) who have loved and supported me for as long as I can remember. To my sister (Maneishi) and my brother (Vishal) for their love, encouragement, and for always being there for me. I also owe a special gratitude to my in-laws (Mrs. Saroj Sinha and Mr. C.P. Sinha) for helping me grow and succeed in multiple ways. I am truly blessed to have all of you in my life.

- Finally, I thank all my friends, especially Seema Verma, Toral Kapur, Preetha Prabhu, Smita Doshi, Kris Wittigen, and Cathy Silbaugh, who have supported and helped me during the PhD program and have remained great friends despite my being a poor correspondent at times.

I dedicate this dissertation to The Lotus Feet of the Divine Mother. It is the will of God and the divine blessing that has given me the opportunity and the wisdom to pursue the doctoral studies successfully. Despite numerous obstacles and difficult times it is the undoubting faith and God's blessings that have helped me come thus far. I am extremely grateful and thankful for everything that I have been blessed with. I sincerely hope I am able to meet the expectations set forth for me.

TABLE OF CONTENTS

CHAPTERS

LIST OF FIGURES Page

LIST OF TABLES

Page

CHAPTER 1

INTRODUCTION

Healthcare forms an indispensable constituent of the modern society, representing a large percentage of Gross National Product (GNP), sustaining a high political profile and strong public interest (Chiasson and Davidson et al., 2004). In the wake of the 21st century, healthcare systems around the globe are faced with exponential rise in expenses, heavy utilization of services due to the steep rise in aging population, and limited financial as well as human resources to deal with the growing needs (Goldberg and Wickramasinghe, 2003), (Varshney, 2005). Current healthcare expenses in US are approximately 15% of the Gross National Product (GNP) (Kern and Jaron, 2003) and are projected to reach 17% of the GNP by 2011 (Boult, 1999), (Chronic Care Improvement). Figure 1 depicts the changing global demographics, the resultant increase in the number of aging *patients*, and the corresponding strain on both the human as well as financial resources of the healthcare sector.

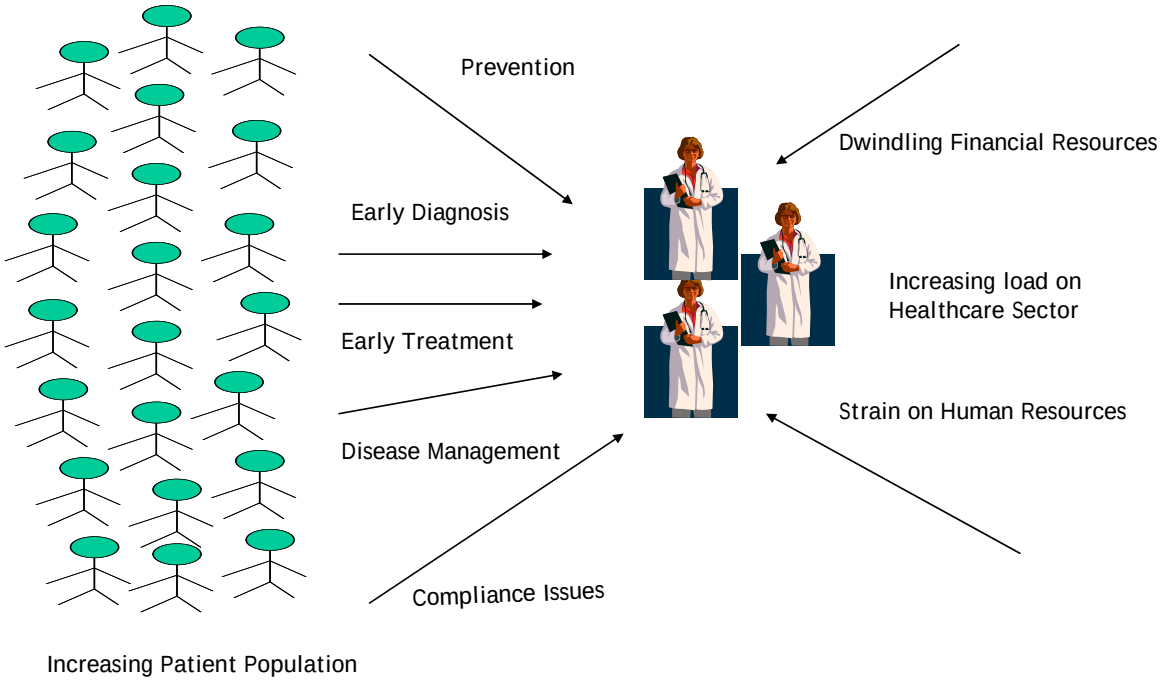


Figure 1: Changing Global Demographics and Resultant Healthcare Needs

The worldwide population of adults over 65 years of age is increasing exponentially and is expected to reach 761 million by 2025 (Tablado et al., 2003). Multiple studies in the past have noted the prevalence of multiple ailments in the aging population – seven of the most prevalent illnesses in U.S. (and their associated in-patient expenses) include: coronary artery diseases ($25.6 billion), heart failure ($15.2 billion), chronic obstructive pulmonary diseases ($6.2 billion), mental health disorders ($3.9 billion), diabetes ($3.8 billion), hypertension ($3.2 billion) and asthma ($1 billion) [6]. A large percentage of these ailments deteriorate to the point where a crisis is reached resulting in unnecessary long term hospitalization at massive costs to the healthcare sector. Many of such crisis situations are preventable and huge cost savings and improved healthcare can result from early detection of complications and proactive management of chronic diseases (Kunze et al. 2002). It is to be noted that often the development of crisis is not due to improper treatment of the patients *inside the hospitals* but is due to inadequate monitoring of patient conditions, lack of proper disease management, and non-conformity with physicians' advice *outside the hospitals.* Many healthcare experts agree that current Medicare expense patterns - approximately 78% of all healthcare spending or well over a trillion dollar per year - are a reflection of *unsuccessful management of illnesses outside the hospitals* (Boult, 1999), (Hunter, 2000), (Chronic Care Improvement).

A critical inference drawn from epidemiological data and past studies is that preventing occurrences of *acute episodes* holds the key to providing *quality healthcare,* reducing incidences of *prolonged hospitalizations* and resultant *healthcare expenses*. In order to reduce preventable acute episodes from occurring it is critical to focus on preclusion of crisis/complications, proactive management of chronic illnesses, and timely detection of anomalies such that patients can lead a normal, healthy lifestyle *outside* of the hospitals.

Innovative strategies are needed to tackle the spiraling healthcare expenses and to cater to the healthcare needs of an aging population in addition to sustaining the trend towards an independent lifestyle focusing on personalized non-hospital based care (Tablado et al., 2003), (US Administration on Aging Reports). One strategy is deployment of a large number of trained healthcare professionals to handle the current healthcare scenario. However, there are two key constraints associated with heavy utilization of human resources: (1) healthcare professionals are limited and over-worked; (2) human resources constitute the most expensive variable in the healthcare sector. Thus heavy utilization of human resources will not only increase the cognitive overload of the healthcare professionals it might lead to higher costs.

Dependable and comprehensive monitoring solutions enabled by information communication technologies for short/long term monitoring of patients at homes, nursing homes, and hospitals is increasingly seen as a viable strategy to: (1) *complement* and *assist* healthcare professionals in *efficiently* managing chronic illnesses, (2) *reduce* incidences of unnecessary *hospitalizations* due to undetected complications*, (3) provide timely detection* of anomalies before it snowballs into a crisis*,* and (4) *provide* pertinent *medical attention* utilizing the expertise of the healthcare professionals for handling anomalies *"just-in-time"* as and when needed without time and/or location dependency (Varshney and Sneha, 2005), (Chiasson and Davidson et al., 2004), (Gouaux et al., 2003). Despite the promises and potential benefits associated with comprehensive monitoring of illnesses outside the hospital, the problem of providing dependable networking support to enable monitoring of mobile patients without time and location dependency has yet not been fully solved. The current research takes a step towards that end by exploring the potential of employing mobile ad hoc wireless networks in conjunction with existing infrastructure oriented wired/wireless networks for comprehensive patient monitoring.

PROBLEM STATEMENT

In the recent past, research and development communities have given considerable attention to understanding and developing innovative patient monitoring applications and research prototypes for accurately monitoring patients' vital signs and timely detection of anomalies (Varshney, 2004). Notwithstanding is the fact that wireless networks are not 100% dependable and inherently suffer from several drawbacks (Malloy, 2002). However, most patient monitoring solutions have *assumed* the dependability of wireless networks and have fully relied on infrastructure oriented wired/wireless networks for signal transmission and comprehensive monitoring of mobile/stationary patients both indoors and outdoors. This reliance on infrastructure based wired/wireless network creates several key issues thwarting the quality and dependability of patient monitoring solutions. The spotty coverage of existing infrastructure oriented wired/wireless networks (such as cellular networks and wireless LANs) due to time and location dependent channel quality and signal attenuation results in permanent/temporary dead spots and can consequently lead to unpredictable quality and reliability of monitoring solutions (Varshney, 2004). Figure 2 depicts some of the issues and challenges associated with sole dependence on infrastructure oriented wired/wireless networks.

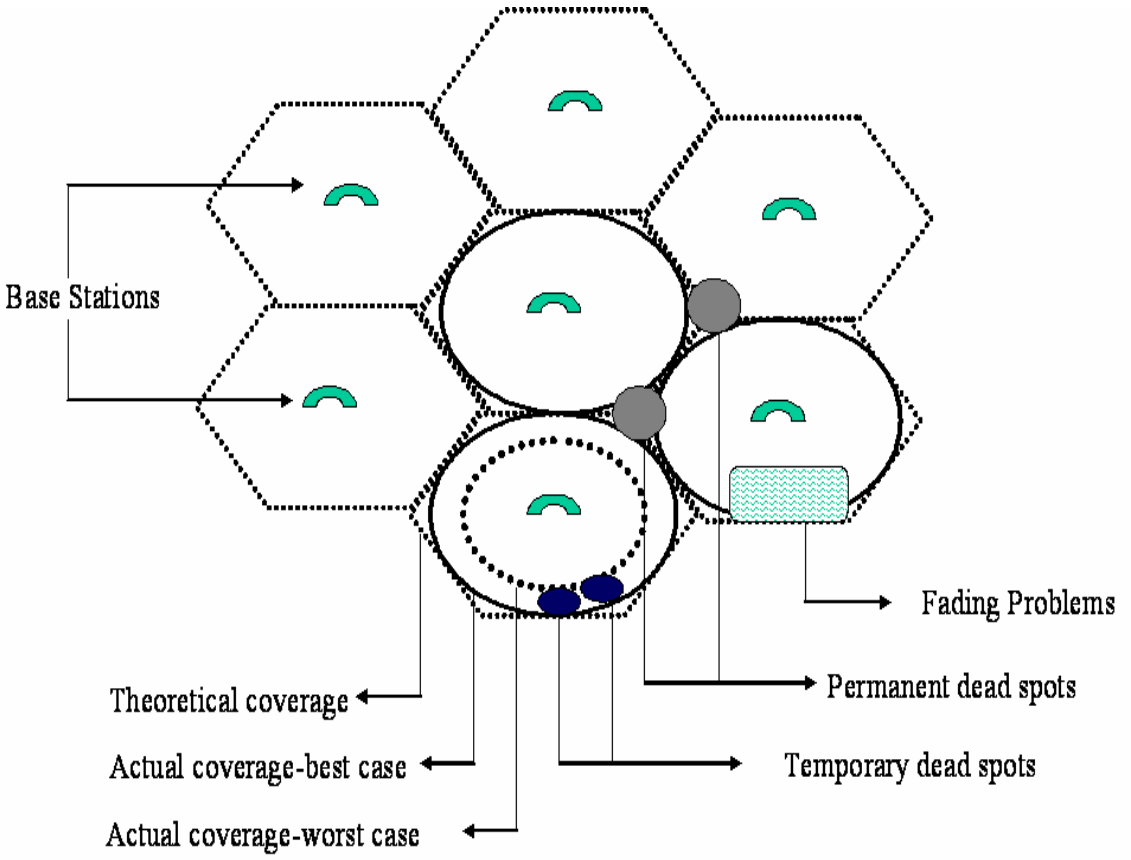


Figure 2: Issues with Exclusive Dependence on Infrastructure Oriented Networks

(Adapted from Varshney, 2004)

The exclusive dependency on infrastructure-oriented wireless networks for patient monitoring has additional challenges including:(a) short range, limited power capabilities, and asymmetry among most patient devices, (b) lack of interoperability among multiple wireless LANs, (c) considerable interference in industrial, scientific and medical (ISM) radio bands from multiple sources - ISM bands were originally reserved internationally for the use of RF electromagnetic fields for industrial, scientific and medical purposes other than communications and in general communications must accept any interference generated by

ISM equipments, (d) varying capacity of infrastructure-oriented wireless networks, and (e) lack of application-specific priority for transmission of emergency signals.

The aforementioned constraints combined with a lack of comprehensive coverage of infrastructure-oriented wireless networks negatively affects the quality of patient monitoring, greatly limits the mobility of patients, and can potentially lead to fatal consequences (Varshney 2004). The need for ubiquity and dependability in patient monitoring solutions combined with the lack of comprehensive support provided by infrastructure oriented wireless networks creates a rich problem space. The current research is motivated in this problem space and explores the novel approach of employing mobile ad hoc network (MANET) in conjunction with existing infrastructure oriented wired/wireless networks to support dependable, comprehensive patient monitoring solutions. A MANET can be formed as and when required among wearable patient monitoring devices capable of routing as well as transmitting signals. A patient monitoring solution based on MANET does *not* intend to replace infrastructure oriented wired/wireless networks *instead* it seeks to complement the coverage of such networks in areas where the coverage from the latter is limited or unavailable, thereby enhancing the coverage and dependability of wireless networks for signal transmission in the context of patient monitoring solutions.

PATIENT MONITORING VIA MOBILE AD HOC NETWORK: ENVISIONED USAGE SCENARIO

Consider the following scenario of patient monitoring where the task of signal transmission from the patient to a healthcare professional is substantiated solely via an infrastructure oriented wireless network.

A nursing home houses patients where they are continuously monitored for detection of any anomalies related to their respective illnesses. "X" is one of the patients living in the nursing home. He is monitored for detection of any anomalies related to a cardiovascular disease via a monitoring device. The device measures electrocardiogram (ECG) readings at pre-specified intervals, processes and analyzes the readings, and wirelessly transmits alerts to a healthcare professional when an anomaly is detected. On receiving the alert the healthcare professional (physician/nurse on duty) provides pertinent medical attention to the respective patient. The network support for alert transmission is provided via a Wireless Local Area Network (WLAN). Due to incumbent shortage of nurses at the nursing home, a nurse physically examines the patient once every hour irrespective of the absence of an anomalous event. At one point during the day "X" goes to the restroom, suffered a fatal cardiac arrest and died in the restroom. An hour later when the nurse came to examine "X" she realized that he was already dead. Later investigation of the monitoring device brought to the attention the fact that the device detected the anomaly in ECG readings and made several attempts to transmit an emergency alert to a healthcare professional. Unfortunately, the alert could not be transmitted because the restroom where "X" suffered cardiac arrest happened to be in a dead spot with no wireless network coverage.

The fatal outcome of the preceding patient monitoring scenario can thus be attributed to the lack of comprehensive wireless network coverage in the nursing home. The spotty coverage of the wireless network in this case resulted in *compromising* not only the

dependability of *patient monitoring solutions* but also *prevented* pertinent *medical intervention* from reaching the patient when required. An extension of the preceding scenario is presented next and graphically depicted in Figure 3. In the following scenario we assume that the patient monitoring devices are capable of forming a mobile ad hoc network to complement the coverage of an infrastructure oriented wired/wireless network when the coverage from the latter is limited or non-existent.

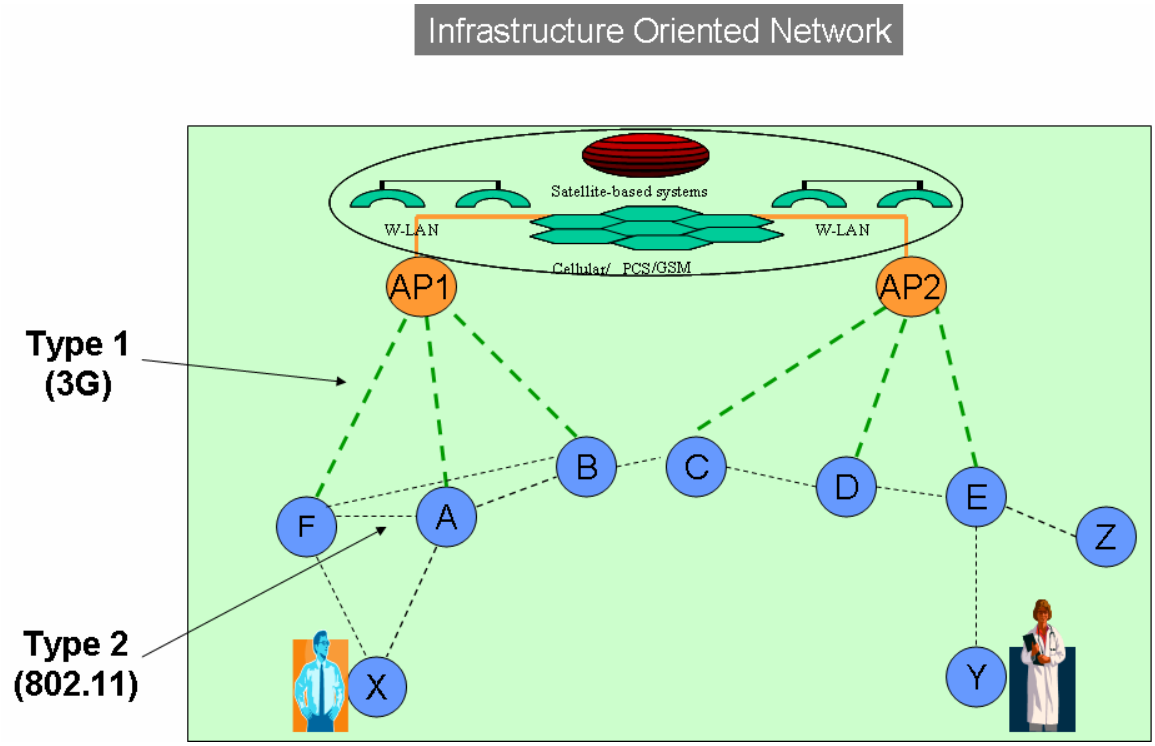


Figure 3: Use of Ad Hoc Wireless Network for Patient Monitoring

……At one point during the day patient "X" goes to the restroom and suffered a cardiac arrest. The patient's monitoring device analyzes the ECG readings (the ontology for which is built in the device specific to the

patient) and detects an anomalous event which requires transmission of an emergency alert to a healthcare professional. The device failed in transmitting the alert via the WLAN since the restroom happened to be in a dead spot with no wireless coverage at the time of the incidence. In the absence of wireless coverage, the patient's device "X" forms an ad hoc wireless network with the other nearby devices by transmitting a strong burst of signal which is picked up by other patient devices, "F" and "A", at a distance of 'd' units. The devices transmit the alert further. The transmitted signal can be routed by an infrastructure oriented network in conjunction with a multi-hop MANET or purely by a MANET such that after multiple hops the alert reaches a healthcare professional "Y". The transmitted alert consists of the location of the patient along with the nature of emergency. The healthcare professional rushes to the patient's location and finds him in the restroom. Immediate medical intervention was provided to the patient as required "just in time". The patient is resuscitated and the crisis is avoided. The physician adjusts the patient's medications and gives few critical advices to patient "X" in order to manage the ailment going further.

In the preceding scenario, *comprehensive network coverage* was one of the critical factors that led to dependable patient monitoring and prevention of a potentially fatal event. Figure 3 shows that signal transmission from the source "X" to destination "Y" can be routed via a pure MANET (i.e. X-A-B-C-D-E-Y) or a MANET in conjunction with an infrastructure (INF) oriented network (i.e. X-A/F-INF-E-Y). Notwithstanding is the fact that the current study doesn't make any claims to undermine the expertise of healthcare professionals in providing medical intervention and/or saving lives nor does it seek to replace the healthcare sector,

physicians, nurses, and other related staff. The research on the other hand seeks to *economize* and *assist* healthcare professionals in providing medical intervention as and when needed, without any delay via *dependable patient monitoring solutions*.

RESEARCH QUESTION AND RESEARCH OBJECTIVE

The proposed approach of complementing the coverage of infrastructure oriented wired/wireless networks by leveraging multi-hop MANET formed among patient monitoring devices holds colossal promises not only for millions of patients requiring long term monitoring and confinement due to prolonged hospitalizations but also for the "health" of the healthcare sector in general. Nonetheless, there are also numerous challenges associated with leveraging mobile ad hoc network to support *dependable* patient monitoring solutions. The current study specifically focuses on the three primary factors underlying dependable patient monitoring solutions via multi-hop MANET:

- *Power management of the battery constrained, low-powered monitoring devices* – Power management is vital to monitoring as well as transmitting signal via multi-hop MANET. The metric for power management in the current research is defined as the total power consumption in signal transmission from the patient to a healthcare professional via multiple hops (i.e. end to end power consumption).
- *Reliability of signal transmission from the patient to a healthcare professional* – Reliability in signal transmission holds the highest priority in the context of patient monitoring via a multi-hop MANET. Reliability can be addressed from multiple perspectives. The definition of reliability adopted in the current study pertains to the probability with which a signal can be transmitted from the source (patient) to the

recipient (healthcare professional) in a multi-hop MANET (Cho et al., 2003). Reliability at each intermediate hop is measured in terms of probability of finding a cooperative router (a device capable of transmitting signal further till it reaches the final recipient) at each hop. It follows that the probability of finding cooperative routers at each successive hop in end to end signal transmission is the metric for end to end reliability of transmission.

- *Delays in signal transmission from the patient to a healthcare professional* – Patient monitoring has bounded delay requirements and the level of delay tolerance can vary from high to low for diverse scenarios. End to end delay is the metric for delay in signal transmission from the patient to a healthcare professional via multiple hops.

Hitherto, a dependable patient monitoring solution via multi-hop MANET is defined as *optimizing end to end power consumption for a given patient monitoring scenario such that the reliability of end to end signal transmission is enhanced at minimal delays in end to end signal transmission*. It follows that the parameters defining dependable patient monitoring in the context of signal transmission via a multi-hop MANET include: end to end power consumption, end to end reliability, and end to end delays. The attributes that characterize various patient monitoring scenarios are as follows: patient/device density in a given transmission area, transmission area, transmission range, patient mobility resulting in uniform versus clustered device distribution, variation in the size and number of clusters in the transmission area, nature of transmitted signal – emergency versus routine, and delay tolerance for message transmission – low delay tolerance (as in emergency messages) versus high delay tolerance (as in routine messages). End to end signal transmission refers to signal transmission from the source to destination via multiple intermediate nodes. Given the current context the primary research question addressed by the current research is:

"How can power of the monitoring devices be efficiently managed so as to achieve dependable patient monitoring solution (as defined in the current research) for various patient monitoring scenarios (as defined by the aforementioned patient monitoring attributes)?"

This study follows the design research methodology which seeks to create and evaluate IT artifacts (Hevner et al. 2004). Following the design science paradigm the goal of *concurrently achieving the conflicting requirements of minimizing power consumption of the low powered monitoring device while maximizing reliability and minimizing delays in end to end signal transmission for a given patient monitoring scenario* is tackled by the following research objectives. It is to be noted that the current research is exploratory in nature and seeks to assess the feasibility of applying MANET for supplementing the spotty network coverage of infrastructure oriented networks such that the quality and dependability of end to end transmission in the context of patient monitoring applications is enhanced.

1. Analyze the dependability of patient monitoring via multi-hop MANET by analytically modeling and evaluating the performance of end to end power consumption, end to end reliability, and end to end delays in signal transmission for diverse patient monitoring scenarios (characterized by its attributes such as: patient/device density in the area of transmission, transmission area, patient mobility resulting in clustered versus uniform distribution, system utilization, processing capacity of the devices).

2. Explore and develop techniques for power management of the monitoring devices. The current study specifically achieves this objective by:

- Developing protocols for power management of the patient monitoring devices at the transmit state (i.e. when the devices are involved in active transmissions). The power-reliability-delay protocols (i.e. PRD protocols) utilize variable-rate transmit power to manage the power transmitted by the source and the intermediate routing devices such that reliability is maximized in end to end signal transmission for diverse patient monitoring scenarios.
- Assessing and investigating the applicability of sleep strategy to conserve power consumption at the idle state (when the devices are listening to transmissions from other devices but are not actively involved in transmissions) without adversely impacting the dependability of patient monitoring in the context of multi-hop MANET.

3. Explore and develop technique for achieving dependable patient monitoring solutions (i.e. minimizing power consumption for a given patient monitoring scenario such that reliability is maximized and delays is minimized in end to end signal transmission). The current study specifically achieves this objective by:
   - Developing a scheme (patient monitoring-power-reliability-delay i.e. PM-PRD scheme) that (a) analyzes a given patient monitoring scenario (as defined by its attributes) and (b) operationalizes a power management technique (i.e. specific power management protocol and/or sleep strategy) with the goal to minimize end to end power consumption, maximize end to end reliability, and minimize end to end delays in signal transmission for a specific patient monitoring scenario. The scheme assumes that the patient monitoring devices receiving/hearing a transmitted signal are cooperative routers.

4. Following the design research guidelines outlined by Hevner et al. (2004), analytical modeling technique is used to assess the validity of the research artifacts in maximizing reliability while minimizing power usage and delays in end to end signal transmission. Specifically the following tasks are achieved:
   - Develop a mathematical model representing end to end signal transmission in diverse monitoring scenarios via a multi-hop MANET. The PRD protocols operationalized in the PM-PRD scheme are analytically expressed in terms of the key independent and dependent variables.
   - Develop diverse scenarios of interest by varying the independent variables.
   - Evaluate/assess the impact on the dependent variables for various patient monitoring scenarios in terms of the performance of reliability, power usage, and delays in end to end signal transmission.
   - The performance of the dependent variables is assessed *before* and *after* leveraging the PRD protocols in end to end signal transmission. The performance evaluation of reliability, power usage, and delays in end to end signal transmission *without* the PRD protocols seeks to validate the relationships of the independent variables on the key dependent variables in diverse scenarios. On the other hand the performance evaluation of reliability, power usage, and delays in end to end signal transmission *with* the PRD protocols seeks to demonstrate that the PRD protocols maximize end to end reliability in signal transmission under diverse monitoring scenarios.
   - The evaluation of the PM-PRD scheme is achieved by: (a) assessing the performance of the PRD protocols under diverse monitoring scenarios (b) discovering the best PRD protocol for a given monitoring scenario such that reliability is maximized while power usage and delays are minimized. The results of the performance evaluation

of the PRD protocols is leveraged to demonstrate the utiity and accuracy of the PM-PRD scheme in achieving the desired objectives.

- Discuss and present the results of the evaluations and analysis.

5. The end to end delay is analytically modeled using M/M/1 Queue for varying patient monitoring scenarios (as defined by varying its attributes). The evaluation of the PM-PRD scheme with respect to end to end delay is associated with the performance of end to end delays while utilizing the PRD protocols under diverse scenarios.

CONTRIBUTION TO RESEARCH AND PRACTICE

The implication of patient monitoring enabled by information communication technologies has been widely recognized as an instrument to contain healthcare expenses, to efficiently manage diseases, to reduce complications and unnecessary hospitalizations. However, the promises of patient monitoring haven't been fulfilled yet and the widespread adoption of patient monitoring applications has been largely limited due to low levels of dependability of existing infrastructure oriented wired/wireless networks. In order to fully reap the benefits of patient monitoring it is imperative to improve the networking support required for comprehensive patient monitoring. Thus far the networking support for patient monitoring is limited to infrastructure based wired/wireless networks which inherently suffer from unpredictable performance and spotty coverage. This study will extend the existing body of knowledge in the areas of patient monitoring and ad hoc wireless networks.

The key significance of the current research is its contribution in investigating the potential of multi-hop MANET formed among patient worn devices as a possible solution to the problem of achieving dependable network coverage for comprehensive patient monitoring. The results show that it is possible to achieve efficient power utilization, 100% reliability of end to end transmission at minimal delay in the context of patient monitoring via multi-hop MANET. Transmissions with relaxed delay and reliability requirements can take advantage of higher power saving while lower delays and higher reliability can be met at the cost of higher power utilization. The relevance of this research extends not only to the community of wireless networking researchers, and practitioners but also to the healthcare community in general. The results of the current research are likely to open multiple doors and avenues for further research in this largely uncharted domain. Some of the unique contributions of this research are as follows:

- It is believed (to the best of my knowledge) that this is the first study that (a) investigates the applicability of multi-hop MANET to complement the infrastructure based wired/wireless network for comprehensive patient monitoring without any dependency on time and location, (b) designs and validates protocols for power management (PRD protocols) of the low-powered monitoring devices with the objective to maximize reliability, and (c) designs and validates the PM-PRD scheme that assesses a given monitoring scenario and operationalizes the PRD protocol with the objective to minimizing power usage and delays in addition to maximizing reliability.

- The PRD protocols are based on variable rate transmit-power with the goal to efficiently utilize the battery power of the monitoring devices. A strategy to implement sleep mode among the monitoring devices is also proposed for efficient power management. The PM-PRD scheme integrates the PRD protocols to the context of patient monitoring by

operationalizing the best protocol for a given monitoring scenario such that the desired goals are met.

- Development of an extensible analytical model, analysis, and performance evaluation of the primary research artifacts (i.e. power management protocols and scheme for dependable patient monitoring) for diverse patient monitoring scenarios.

- The results corroborate that the research artifacts can be leveraged in end to end signal via a multi-hop MANET to complement the coverage of infrastructure oriented networks and thereby enhance the quality and dependability of patient monitoring applications.

The primary artifacts developed in the current research have the potential to sustain: (a) broadcast routing scheme for emergency as well as routine transmissions, (b) diverse reliability requirements such as: highest reliability for emergency transmissions and relatively lower for routine transmissions, (c) diverse monitoring and transmissions such as: alert, continuous, and periodic, (d) diverse location and mobility such as: indoor/outdoor and stationary/mobile patients, (e) scalability requirements – the mobile devices transmitting signal in a multi-hop MANET act as routers thus reducing the load of routing on the base stations when large numbers of messages are being transmitted concurrently, and (f) location management via technologies such as RFID (radio frequency identification) and GPS (Global Positioning System) incorporated in the patient's device. The analytical model developed for this study is extensible and can serve as a platform for conducting future studies pertaining to this area by researchers in the field of wireless networking to develop and model future researches.

Future research can explore other key factors that are also important constituents of patient monitoring via multi-hop MANET such as: efficiency in routing, mobility model for patients, throughput, and interference. As the industry gets more competitive, the infrastructure providers are likely to venture in the realm of utilizing ad hoc wireless networks to optimize the network performance and provide quality service to the users.

As the pressure on the healthcare sector increases, it will find innovative ways to provide healthcare services to the ever increasing patient population. Since the proposed research is the first to the best of my knowledge to explore the potential of multi-hop MANET for comprehensive patient monitoring it can be the harbinger of future researches to support extremely dependable patient monitoring solutions. The results of the current study have the potential to implicate significant changes in the way patient monitoring is practiced and delivered. It holds the promise of: (a) improving quality of healthcare and lifestyle of millions of people suffering from multiple diseases by allowing them to lead an independent, healthy lifestyle outside of the hospitals (i.e. at homes, nursing homes, assisted living communities) while being continuously monitored for detection of anomalies, (b) economizing and effectively utilizing the human resources of the healthcare sector by obtaining their attention "just in time", as and when needed, and without any delay, (c) reducing unnecessary fatalities and hospitalizations associated with manifestation of crisis due to undetected anomalies, and (d) corresponding reduction in healthcare expenses associated with unnecessary hospitalization and mis-management of chronic diseases. The healthcare sector will benefit largely from the reduction in hospitalization expenses, early detection of anomalies, and the corresponding reduction in the stress on healthcare professionals. Moreover, development of innovative services focusing on dependable patient monitoring could result in new jobs and research spanning growth in the technology, engineering,

management, and healthcare sector. Thus the innovation in healthcare service industry can turn into a growth engine creating economic advancement and prosperity. It is to be noted that the current research does not seek to *replace* the healthcare professionals' healing touch and/or medical expertise associated with providing quality healthcare. On the contrary it seeks to *complement and assist* the healthcare professionals in provision of prompt medical intervention to patients as and when needed.

DISSERTATION OUTLINE

The organization of the remaining chapters in the dissertation is presented next. Chapter 2 presents basic background knowledge on the concept and requirements of patient monitoring. Additionally, this chapter also presents an overview of the evolution of previous research in the domain of patient monitoring followed by a discussion of strengths and limitations of prior work. The concept of multi-hop MANET, the advantages/disadvantages, and background information pertaining to prior research in reliability and power management are presented in Chapter 3 and discussed and compared with the objective of the current study. Chapter 4 presents the details on the primary artifacts in the current study: the power management techniques and the scheme for achieving dependable patient monitoring for any given patient monitoring scenario. Chapter 5 provides details on the research methodology and the research model that are used within the research study. Chapter 6 presents the analytical model utilized in the current study for evaluation purposes along with selected results. Finally, conclusion, limitations of the current research and future research are discussed in Chapter 7.

CHAPTER 2

PATIENT MONITORING

Patient monitoring is an age old concept which has evolved over the years. Traditionally patient monitoring implied monitoring of specific patient conditions by leveraging human resources in order to provide correct diagnosis and treatment. However, for the traditional form of monitoring patients to be sustainable, a larger workforce along with a bigger financial support is imperative. Under the dwindling financial and human resources available at the disposal of the healthcare sector technology based patient monitoring solutions is increasingly viewed as a viable option for meeting the healthcare needs of the changing global demographics and focusing on prevention of crisis, timely detection of anomalies, overall wellness, and proactive disease management.

The underlying covenant of technology enabled patient monitoring services is that prompt medical attention will be provided to the patients "just-in-time" as and when required without any constraints based on time and location. Comprehensive patient monitoring outside the hospitals will not only reduce the healthcare expenses associated with hospitalizations but will also allow precious human resources to be allocated to the healthcare needs of other patients. Patient monitoring typically involves: (1) *recording* specific vital signs such as ECG, oxygen saturation level, body temperature, blood pressure, and heart rate, and patient parameters and information such as skin breakdowns, abnormal gait and balance, motor activity and agitation, current location, weight, cigarette smoke, and the amount of moisture in clothes and/or levels of physician specified chemicals as in cancer treatment, (2) *analysis* of recorded vital signs, and (2) *transmitting* the data via a communication network (wireless or wired).

PATIENT MONITORING REQUIREMENTS

The requirements of patient monitoring are not only diverse supporting indoor and outdoor, as well as stationary and mobile patients but are also complex, and involve multiple parameters such as: duration of monitoring, frequency of data collection and transmission, amount of data transmitted, nature of monitoring such as: alert, periodic or continuous. The following overview of the requirements of patient monitoring shows the complexity, diversity, and somewhat contradictory nature of the requirements. Figure 4 graphically depicts a conceptual classification of the diversity and complexity of patient monitoring requirements.

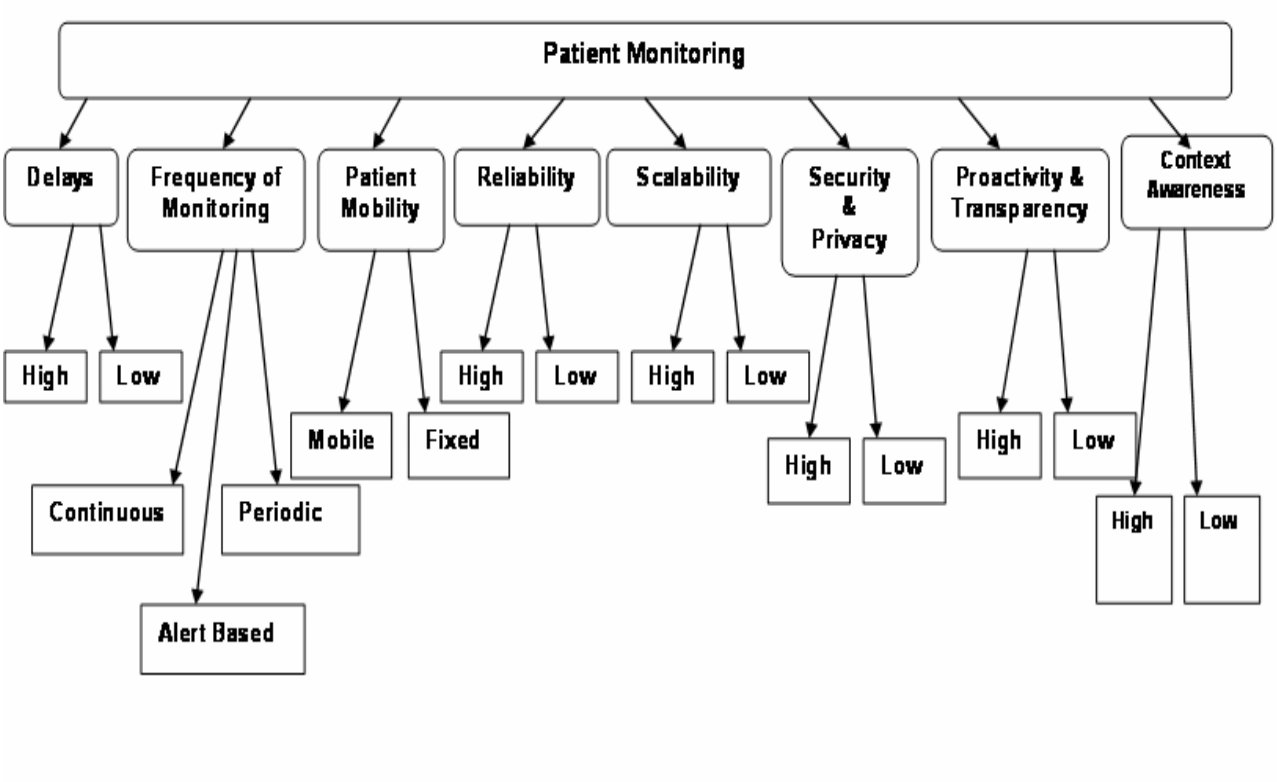


Figure 4: A Conceptual Framework Classifying Patient Monitoring Requirements

Monitoring and Transmission: Patient monitoring can be continuous, alert driven (on the detection of an abnormal event) or periodic (at fixed times in a day). Continuous monitoring and transmission can provide real-time data for analysis and storage but can also lead to an information overload of healthcare professionals and significant network traffic (such as patients undergoing critical care). Periodic monitoring and transmission sacrifices the real-time aspect for a decrease in network traffic and information overload and is suitable for patients under routine supervision. In alert driven monitoring, the patients are continuously monitored and the acquired data is analyzed for detection of anomalies. Only when an anomaly is detected and medical attention warranted, is a message transmitted over a network. This type of monitoring could result in a time lag in performing analysis and sending alert messages, however, a reduced information load and network traffic make it a possible choice in some instances of patient monitoring.

Reliability of Message Delivery: Due to the potentially life threatening situations, reliability of message delivery to healthcare professionals is the most critical requirement of patient monitoring. Routine transmission of signals from a patient can tolerate low reliability while emergency messages have the highest reliability requirement. Thus different monitoring messages can be prioritized based on the reliability requirements. The factors impacting reliability in infrastructure and ad hoc wireless networks based solutions include: network coverage, presence of dead spots, device range, available power, bit rate, routing protocol, failure(s) in the network or device, and un-cooperative behavior of other devices.

Reasonable Time in Message delivery: Any delay in message delivery can have fatal consequences. The priority of transmitted message (emergency or routine) can be used to determine the routing of messages by a network to reduce delays, which may be substantially

impacted by frequency of monitoring, size of message transmitted, bit rate, and the number of monitored patients. The objective is to have minimum delay in end to end message delivery.

Power Conservation: Power management of the low powered monitoring devices with diversity in the range of functionality and computing capabilities used for signal transmission poses a challenge in providing reliable patient monitoring solutions**.** The battery (power source for most wearable devices) typically forms the heaviest component; hence there is a tradeoff between carrying a heavy device and the frequency of recharging the battery. The critical factors impacting utilization of power include the frequency and size of transmitted messages and routing schemes employed for message transmission.

Support for Mobile Patients: patient monitoring solutions should be able to support mobile patients indoor and outdoor. Patient mobility results in patients moving in and out of network coverage (in an infrastructure based network), thus negatively impacting reliability in patient monitoring. Hence the challenge is to design dependable networking support for monitoring both mobile and stationary patients. Ad hoc wireless network can be a potential solution.

Scalability: The patient monitoring network must scale well in terms of the number of monitored patients that can be reliably supported. The factors influencing scalability are: bit rate, frequency of monitoring and transmission, and the amount of information transmitted per patient.

Reasonable Cognitive Load for Healthcare Professionals: Analyzing continuous streams of data from monitored patients and making relevant diagnosis can be an arduous task for the healthcare professional. It can also impact network traffic and scalability of the solution. A solution is to utilize the computational capabilities of the monitoring devices for initial analysis and decision making, and alerting the healthcare professionals only when an anomaly is detected.

Confidentiality, security, and privacy: As healthcare information is being transmitted over wireless networks, efforts should be made to keep it confidential and private. Privacy entails the right of a user to control the collection and dissemination of personal information and security is the protection of user's information from unauthorized users. Privacy and security are one of the key challenges towards large scale adoption and diffusion of ubiquitous computing empowered by wearable devices (US Administration on Aging Reports). This is expected to be one of the most critical requirements for healthcare administrators and government regulators.

Proactivity and Transparency: Proactivity and transparency refers to the intelligence in the monitoring device/environment which will be able to sense the current intent of the patient and proactively take certain actions on behalf of the patient. For instance: if the device senses that the patient's ECG has gone beyond a pre specified threshold then the intelligence in the device may want to alert the doctor of the situation and schedule an appointment as soon as possible along with informing the patient of the appointment. But this proactive action should be transparent to the patient as far as possible. Proactivity should not become a source of annoyance.

Context awareness: Context awareness is in synch with proactivity since a patient monitoring environment cannot be proactive in assisting a user in decision making unless the right context information is available. For instance: if the patient's heart rate has gone up then the device must be aware of the context where and when the heart rate was high. If the patient was watching an exciting football game which caused the heart rate to go up while the vital signs from other sensors were within the normal range then the device should be able to detect the context and not send alerts. Context information can be recovered from sensors and would essentially contain information about who, what, when and where.

Table 1 presents the requirements and/or challenges associated with patient monitoring along with the various decision factors which characterize each requirement.

Table 1: Requirements, Decisions, and Technology Supporting Patient Monitoring

REQUIREMENT	DECISION CRITERIA AND ENABLING TECHNOLOGIES
Monitoring	What to monitor – BP, ECG, Body Temperature, Blood Oxygen Level etc. When to monitor – Periodically (what time interval), Continuously How to monitor – Via sensors, physically separate devices ex: thermometer, BP Monitor.
Analysis	Analyze the Collected Information Before Transmission? What to Analyze – The vital signs, the compliance factors etc. How to Analyze – Based on Stored Thresholds, Standardized Data How/What to Transmit – Which Network, Patient's Location, Current Reading,
Transmission	What to transmit – complete recorded data, differential data, personal information How to transmit – WLANs, Cellular PCS/GSM etc., or ad hoc wireless networks When to transmit – Periodically, continuously, alert based
Reliability	Reliability in sensing, analyzing and transmitting patient information via built in redundancy Varying Reliability Levels for Transmitted Messages? - High (Emergency), Medium (Routine), Low (Reminders etc.) - Reliability in communication by utilizing multiple communication networks

Delays	Prioritized Transmission. Low– Emergency Transmission, Medium– Routine Transmission
Power Conservation	Mobile computing and communication devices with power conservation methods such as sleep cycles, emergency power reserve, solar energy, innovation in conserving/charging devices.
Support for Mobility	Patients Mobile Indoors/Outdoors? Variation in Mobility Pattern – High/Low speed, Children/Adults
Cognitive Load	The cognitive load on the healthcare professional should be low by automating the analysis as far as possible.
Security, Privacy, and Confidentiality	High levels of security, privacy and confidentiality. Technologies with built in secure authentication processes, secure fool-proof communication resources, biomedical measurement/sensing devices, and patient specific intelligent devices
Proactivity and Transparency	Varying Levels of Proactivity and Transparency? Low Proactivity -> More Input/Low Transparency, High Proactivity -> Low Input/ High Transparency
Context Awareness	High level of context awareness in order to correctly analyze the collected information

REVIEW OF PRIOR WORK IN PATIENT MONITORING

In the recent past, research and development community has given considerable attention to understanding and developing viable patient monitoring applications and research prototypes for accurately monitoring patients' vital signs and timely detection of anomalies (Sneha and Varshney, 2005). At the Center for Aging Services Technologies (CAST) in Washington D.C. (established in 2002), companies including General Electric, Hewlett Packard, Honeywell, and Intel have teamed up to encourage collaborative aging-related technology development and to advocate wireless, remote monitoring of patients, specifically the aging populace that incurs the largest percentage of healthcare expenses.

The current advancement in wireless communication technology including increased communication bandwidth and miniaturization of mobile terminals, along with a parallel advancement in patient worn monitoring devices have together given a boost to monitoring solutions for patients inside and outside the hospital premises (Lin, 2004 #3). It is now possible to record and transmit digitized vitals signs in the form of signals from a patient device to the computer or hand-held PDA of a health care professional instantly, hence reducing the time taken for evaluation and treatment (Gouaux et.al., 2003, Nussbaum, et. al, 2002, Khoor, et. al, 2001, Hung, et al. 2003). However, the degree of reliability and effectiveness in patient monitoring as provided by commercially available portable monitors and research prototypes regarding timely detection of anomalies, and provision of medical attention *as and when needed*, are not satisfactory yet.

Previous research and development efforts in patient monitoring have addressed some of the challenges and requirements of patient monitoring. First generation monitoring service provides restricted mobility and is also limited in terms of comprehensive patient monitoring. It involves collection and transmission of data within a hospital over wireless LANs such as: Micropaq that transmits multi-parametric information via Wireless LANs (Welch Allyn, 2005), and LifeSync (WirelessECG, 2005) which uses short range wireless signals such as Bluetooth to move information within a hospital infrastructure. Next generation monitors, such as Medtronic (Mendoza et al. 2002), allow patients to live in their homes while required data is collected and transmitted at predefined time – end of day or week. Motiva provides disease management and increased quality of life to the patients via a secure, personalized healthcare communication platform that connects chronic patients at home to their healthcare providers through their TV sets and cable systems for IP access (Phillips). Some

monitors provide short term monitoring for 10-14 days with the intention to diagnose a patient's condition to match it with the correct treatment such as: CardioNet, and Biotronik.

A system for real-time monitoring of patients in the home environment is presented by Khoor, et al. (2001), asthma in home monitoring via a video monitor and a secure website for uploading the relevant information is presented by Covington (2001), and unobtrusive wellness monitoring of elders via sensors by IST Vivago Wristcare with automatic alarm triggering capacity and communication over telephone lines (Sarela, 2003). Recently, prototypes and research have focused on providing monitoring solutions to mobile patients. Continuous collection and transmission of vital signs via infrastructure-based wireless network (WLAN, Cellular PCS, and Satellites) is shown by: Liszka, et al. (2005) and Nussbaum and Wu (2002), Sneha and Varshney (2005). Work on other related issues in patient monitoring include "smart health wearable" research (Lymberis, 2003), interference for telemetry devices (Gieras, 2003), PDA as a mobile gateway (Jovanov, et. al., 2002), long-term health monitoring by wearable devices (Suzuki and Doi, 2001), and, smart shirt based health monitoring, a wearable stethoscope (Kyu and Asada, 2002). Clothing-embedded transducers for ECG, heart rate variability, and acoustical data and wireless transmission to a central server are proposed in (Jovanov, et. al. 2002). A requirement model for delivering alert messages is presented in (Kafeza, et. al, 2004). A design approach for data compression for a mobile tele-cardiology model is presented by Istepanian and Petrosian, (2000) who achieved a significant compression ratio and reduction in transmission time over GSM network. Personal health monitors based on wireless body area network (BAN) of intelligent sensors are proposed for stress monitoring (Jovanov, et. al, 2003). Alert Based continuous monitoring of Parkinson patients by intelligent wearable devices is described by Tablado et al., (2003). Empowered by technology promoting ubiquitous computing, there has been some research and

development efforts for intelligent monitoring of patients in context aware, secure, smart environment for assisting elders to living independently, examples include Gator Tech Smart House, Aware Home Project, and Elite Care.

Summarize…….

Transmission of data for patient monitoring has so far been supported by either wired or wireless infrastructure based network. Periodic monitoring in the home environment has been supported via television sets, video monitoring, and two-way broadband connection via cable modem and telephone lines. The wired communication is reliable but doesn't provide support for patient mobility and continuous monitoring. Bluetooth has been utilized for short range wireless communication between the monitoring device and WLANs. Satellite based communication has been used for GPS (Global Positioning System) for outdoor purposes and indoor location tracking is typically supported via RFID (Radio Frequency Identification). WLANs, cellular networks have primarily been used to support continuous patient monitoring along with patient mobility. Signal transmission for patient monitoring solutions predominantly takes place via cable modem, and infrastructure based network such as WLANs, Cellular PCS/GSM, and Satellite based Networks.

This reliance on infrastructure based network is attributable to the assumption that the former provides comprehensive network coverage and is 100% reliable. However, in reality the infrastrucutre oriented networks suffer from spotty, unpredicatable coverage due to time and location dependent channel quality and signal attenuation resulting in permanent/temporary dead spots. This negatively affects the ubiquity and dependability of monitoring solutions. The current research addresses the issue of spotty network coverage of infastructure oriented networks by investigating the potential of utilizing multi-hop MANET to

complement the coverage of infrastructure oriented wired/wireless networks. The objective is to enhance the network coverage such that the quality and dependability end to end signal transmissions in the context of patient monitoring solutions is enhanced.

CHAPTER 3

MOBILE AD HOC NETWORK (MANET)

The objective of the current chapter is to: (a) present an introduction to multi-hop mobile ad hoc network (MANET) and the associated opportunities and challenges, (b) review prior work in reliability and power management with respect to MANET, and (c) derive the key relationships and dependencies with respect to reliability, power usage, and delays in terms of the key independent and dependent variables. The applicability of a multi-hop MANET in the context of patient monitoring is assessed in terms of power management of the patient monitoring devices, reliability, and delays in end to end signal transmission. Power management, reliability and delays are the primary requirements of patient monitoring and hence form the locus of the current research.

A mobile ad hoc network consists of a collection of geographically distributed wireless devices or nodes that can dynamically form a network without a pre-defined infrastructure and communicate with one another over a wireless medium (Jain, S. 2003, Rajaraman, R., Qin, L. et al 2004). The nodes act as routers as well as transmitters. The critical advantages associated with ad hoc networks are: (a) *ease* and *speed of deployment* (since it can function dynamically without any infrastructure), (b) *robustness*, (c) *flexibility* in terms of place of deployment and number of users, and (e) the inherent *support for mobility.* The capability of dynamic deployment without any dependence on infrastructure is a key benefit in situations where the infrastructure has been destroyed due to a large scale catastrophe such as: Tsunami and disaster on "September 11". The aforementioned factors form the cornerstone of deploying multi-hop MANET in the comprehensive patient monitoring since

they afford the mobility of the patients as well as the doctors (Sesay, S. et al. 2004, Vaidya 2006).

The challenges are related to the (a) variations in the mobility pattern and mobility characteristics of the nodes; (b) asymmetric capabilities of the nodes and associated constraints with respect to transmission range, battery power, and processing capacity of the nodes; (c) diversity in traffic characteristics such as bit rate; (d) timeliness constraints; and (e) reliability requirements. Resources such as bandwidth, battery life, storage space, and processing capability are limited in MANETs. Out of these, bandwidth and battery life are very critical resources, the availability of which significantly affects the performance of strategies impacting quality of transmissions based on MANET. Hence efficient resource management strategies are required for optimal utilization of these scarce resources (Reddy et al, 2006). The route from the source to the destination typically involves multiple hops and the route is susceptible to changes due to dynamically varying network topology associated with unrestricted mobility of nodes (see Figure 5).

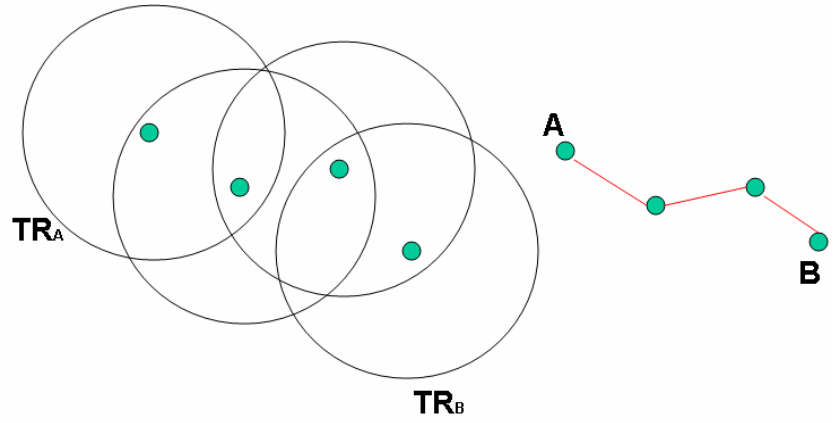


Figure 5: Multi-Hop Signal Transmission in Ad Hoc Wireless Network

Recent advent in personal digital assistants and plethora of mobile patient monitoring devices that are used in transmission of vital signs over short range, have brought to the fore ground the possibility of forming ad hoc networks among patients' devices which can monitor and transmit vital signs to one or more healthcare professionals using a single hop or multi-hop routing mechanism (Rajaraman, R., Varshney, U. 2004). The patient monitoring devices (PMDs) form the nodes in the mobile ad hoc network for the purpose of routing and transmitting signals.

MOBILE AD HOC NETWORK IN THE CONTEXT OF PATIENT MONITORING

The flexibility in deploying a network for signal transmission when the coverage from infrastructure based network is limited or non-existent is of critical importance in the context of patient monitoring (as discussed in Chapter 1). The unique challenges associated with wide scale deployment of ad hoc network for patient monitoring include support for reliability, energy conservation of the battery powered monitoring devices, routing mechanisms, network topology control in a dynamic environment, mobility pattern of the nodes, security, range and signal reception, throughput and bit rates, number of patients that can be supported, and interference, (Jain, S. 2003, Rajaraman, R., Qin, L. et al 2004, Sesay, S. et al. 2004, Giordano, S. et al., Camp, T. et al, 2002). Due to power and size requirements of patients' devices, the range of transmitted signal is likely to be small. Further, the range is likely to be affected both by the frequency of operation, the nature of spectrum used (licensed vs. un-licensed), mobility, and obstacles. The signal strength can be weakened by 30-90% as it passes through doors, walls, and windows depending on the material and construction employed. Additionally, the availability of wireless links varies over space and time due to power loss

caused to a signal. The range is also likely to affect the probability of finding another device that can act as co-operating device for routing in ad hoc networks. The throughput, or actual number of bits that can be transmitted after subtracting overhead and retransmission, decreases as the distance between nodes of an ad hoc network increases. The number of patients that can be supported will depend on the bit rate, frequency of monitoring, and the amount of information per patient that needs to be transmitted every time. One major issue may be the "intermittent" interference present due to other existing sources of ISM bands such as unlicensed spectrum radio, microwave ovens, or radar transmitters affecting the usability and range of ad hoc networks for patient monitoring. Since mobile ad hoc networks operate in a very dynamic environment where every link is wireless and every node is mobile, the resulting topological changes affect the reliability of message delivery.

Among the numerous challenges associated with application of MANET for patient monitoring. The focus of the current research is on efficient resource utilization (i.e. battery power) of the low-powered PMDs with the goal to enhance the performance of reliability and delays in end to end signal transmission. Reliability, delays, and power management of the diverse low-powered mobile PMDs are the most critical as well as conflicting challenges underlying patient monitoring based on a multi-hop mobile ad hoc network and consequently form the focus of the current research.

END TO END RELIABILITY IN SIGNAL TRANSMISSION

Reliability in signal transmission from the source to the destination is an indispensable requirement of dependable patient monitoring solutions due to the potentially

fatal consequences associated with patient monitoring (as discussed in Chapter 2). In the context of patient monitoring based on multi-hop MANET, end to end reliability in signal transmission is utilized as one of the key evaluation metric assessing the performance of the proposed power-reliability-delay (PRD) protocols under diverse patient monitoring scenarios.

Reliability in an ad hoc wireless network can be addressed from multiple perspectives. Prior work done in the area of reliability includes broadcast schemes (Cho, S.Y. et al, 2003), routing protocols (Lou, W. et al. 2003, Kim, J.M. et al, 2001), discussion of the tradeoff between reliability and energy efficiency (Zhu, J et al, 2003), and, increasing reliability by using a receiver-initiated hop by hop acknowledgement scheme (Lou and Wu 2003). Broadcast based routing schemes can greatly enhance the reliability of messages delivery to one or more healthcare professionals; however it results in considerable network traffic from sending messages to all possible destinations, increased interference from transmitting devices and chances of collision. Similarly reliability of transmission to next hop can be increased by multiple retransmissions with hop-by-hop acknowledgements (ACK) but it can result in implosion problem along with creating high levels of network traffic, and consuming more power than necessary (Lou and Wu 2003). The use of multiple ad hoc networks is likely to increase the reliability of message delivery; however the total traffic on all networks could be significant. Increased power transmission will also lead to increased reliability since it increases the range of transmission and thus the probability of finding co-operating routing devices or a healthcare professional. However, the transmitting device may use up all its power quickly resulting in the death of the transmitting node, and adversely impacting the connectivity of the network and consequently the reliability of transmission.

In the prior research reliability has typically been addressed as a function of routing (protocols and schemes) with the performance metric being interference, throughput, bit rate etc. In the current research reliability is approached as a function of power management of the monitoring device forming the nodes in multi-hop MANET with the performance metric being probability of locating a cooperative device/node within the range of a transmitted signal at each consecutive hop in end to end routing of the transmitted message *for a specific patient monitoring scenario.* This approach has been adapted from the definition of reliability presented by Cho et al, (2003). Low probability of locating a cooperative device(s) in end to end signal transmission implies low reliability in end to end transmission and vice-versa for high probability of locating a cooperative device(s) in end to end signal transmission. The critical assumptions is that the patient monitoring device(s) within the range of the transmitted signal are cooperative routers (i.e. the PMD(s) are *willing* and *capable* of transmitting the signal further to the next PMD and so on and so forth till the transmitted signal reaches its destination). The current perspective on end to end reliability concedes that the resource (i.e. battery power) available to the PMDs can be manipulated based on the constraints/requirements associated with diverse patient monitoring scenarios with the goal to enhance the probability of locating cooperative PMDs in end to end signal transmission via a multi-hop MANET.

Reliability in end to end signal transmission varies for diverse patient monitoring scenarios. In the context of the current research diverse patient monitoring scenarios, impacting end to end reliability in signal transmission, are a function of variations in the following parameters: (a) patient/device density in the area of transmission, (b) the transmitted power in signal transmission at each intermediate hop in end to end signal transmission, (c) the patient/device mobility impacting distribution (uniform/clustered), (d)

variations with respect to the clusters in terms of size, number, and (e) the clusters being on/off the route of transmissions. Figure 6 shows a model of the parameters that directly/indirectly impact end to end probability of signal transmission in the context of patient monitoring applications based on multi-hop MANET. End to end probability in signal transmission is a proxy for end to end reliability in signal transmission.

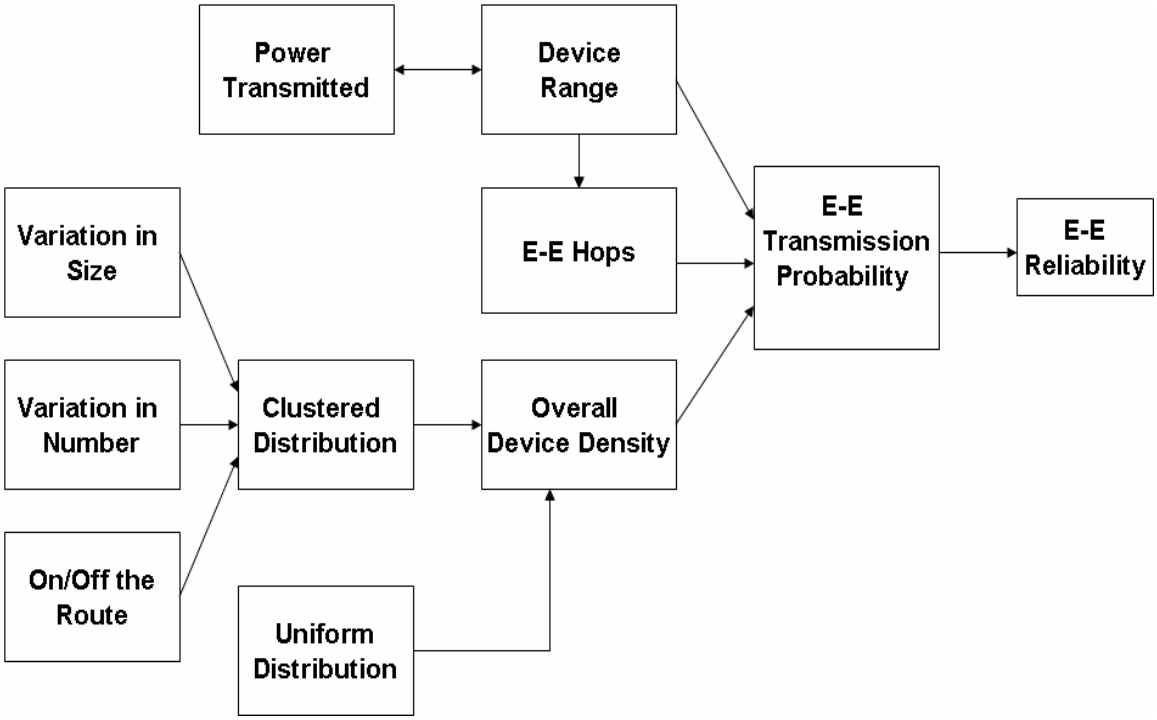


Figure 6: Parameters Impacting End to End Reliability of Transmission

It is to be noted that reliability in end to end signal transmission has been addressed from the perspectives of throughput, network availability, bandwidth, bit rate in prior research. However, a primary requirement associated with the current context of patient monitoring is the probability of locating a cooperative device/node at each hop in end to end signal transmission. One of the key premise in the current research associated with reliability

is the fact that all devices in the area of transmission are cooperative routers. Consequently reliability is directly related to the proabability of locating patient monitoring device within the range of a transmitted signal. Thus reliability in end to end signal transmission in the current research is addressed from the perspective of probability of locating a cooperative device at each hop in end to end signal transmission. The current approach concedes that the existing network characteristics and content is difficult to change. Instead, it suggests that protocols for efficient resource (battery power) utilization may be incorporated and executed such that probability of locating one/more cooperative PMD in end to end signal transmission is enhanced. Table 2 gives a brief overview of the parameters that impact end to end reliability of transmission.

Table 2: Overview of Parameters Impacting End to End Reliability of Signal Transmission

Environmental and Device Level Characteristics	Parameters Impacted	Comments	Constraints and Challenges with respect to End to End Reliability in Transmission
Battery Power	Transmitted Power - Device Range - Number of Hops from Source to Destination	Battery power affects transmitted power from a node. The transmitted power in turn impacts device range. Transmission range of the device impacts the number of hops between the source and destination	The Device Range determines the nodes that can hear a transmitted signal thereby impacting the chances of locating a node for signal transmission. Smaller device range uses less power but reduces the number of nodes that can hear a transmitted signal.
Number of Devices in the Area of Transmission	Device Density	Device density is impacted by the number of devices in the area of transmission.	Higher device density results in higher probability of locating a node for signal transmission for a given level of transmitted power. If the number of hops corresponding to a certain transmitted power = 'H' and if device density ranges from d1 to d7 such that

			d1<d7 Then reliability is higher for d7 than d1
Mobility of Devices	Clustered OR Uniform Device Distribution Clusters - Vary in Size - Vary in Number - Vary in being on/off the route of transmission	Patient mobility causes the devices to group in some areas at some point in time resulting in clusters. The clusters can vary in size, number and the clusters being on/off the route of transmission	Clustering of devices results in decrease of overall device density in the area of transmission while increase in device density within the clusters. This reduction in overall device density negatively impacts reliability for a given level of transmitted power. If the clusters are off the route of transmission, then reliability is further reduced

The requirements for enhancing reliability in end to end signal transmission conflict with the requirements for efficient power management. On one hand higher level of emitted power from the transmitting device results in fewer hops, increased device range, higher probability of locating cooperative PMDs (even at low device density) but on the other hand higher level of emitted power results in higher energy usage, higher interference to the neighboring devices, less efficient routing, reduced throughput, and reduced longevity of the network. Depending on the patient monitoring, and application specific requirements either reliability or power conservation will have to be sacrificed (Zhu, J et al, 2003).

END TO END DELAYS IN SIGNAL TRANSMISSION

Patient monitoring solutions have stringent delay requirements consequently one of the critical requirements of a dependable patient monitoring application is bounded delays in end to end signal transmission (as discussed in Chapter 2). In the context of patient monitoring based on multi-hop MANET, end to end delay in signal transmission is utilized as

one of the key performance measures assessing the applicability of the proposed power-reliability-delay (PRD) protocols for diverse patient monitoring scenarios. End to end delay in the current research is analytically modeled in terms of M/M/1 queue and is addressed from the perspective of total time taken in signal transmission from the source to the destination via multiple intermediate hops.

Patient monitoring requirements dictate variability in the degree of tolerance with respect to end to end delay in signal transmission. The tolerance for end to end delay varies for diverse patient monitoring scenarios (i.e. emergency – low delays, routine – relatively higher delays). The parameters creating diverse patient monitoring scenarios and impacting end to end delays in signal transmission include the following (see figure 7): (a) service rate of the PMDs, (b) system utilization, and (c) end to end hops.

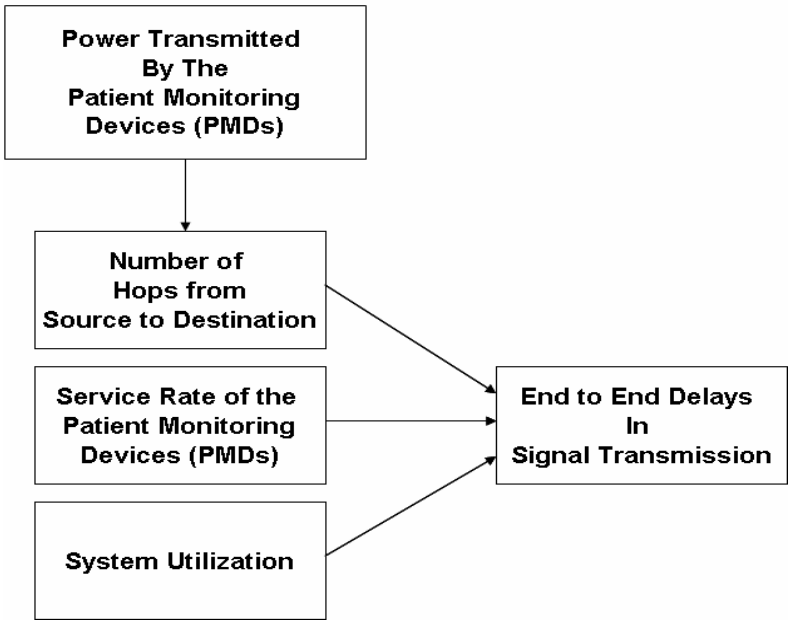


Figure 7: Parameters Impacting End to End Delays in Signal Transmission

The details of the specific parameters impacting end to end delay in the context of signal transmissions via a multi-hop MANET are as follows:

- Service rate or processing capacity of the monitoring device directly impacts the delay in processing a signal by the monitoring device at each hop. Higher the processing capacity of the device lower is the end to end delay and vice-versa. The PMDs involved in end to end signal transmission may/may not be symmetrical with respect to service rate.

- System utilization (i.e. number of messages in the network) has a negative relationship with end to end delays. If the system utilization is high the end to end delay increases proportionately.

- Number of end to end hops is directly proportional to the end to end delay for a given patient monitoring scenario. A PRD protocol resulting in a longer route may have a higher end to end delay compared to another protocol with relatively smaller route. Thus end to end delay in signal transmission increases with an increase in the number of end to end hops. The challenge in minimizing end to end delay lies in striking a balance between minimal hops transmissions versus minimal power transmissions (see figure 8). For instance: emergency transmissions with low delay tolerance require sacrificing efficiency in power consumption for minimal end to end delays.

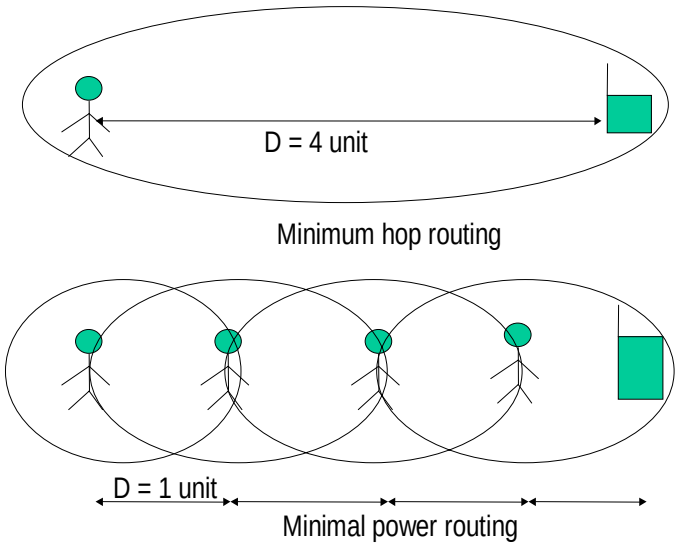


Figure 8: Minimal Delay Transmissions vs. Minimal Power Transmissions

END TO END POWER CONSUMPTION

The performance of applications and services supported via a multi-hop MANET is significantly impacted by the limited battery power available to the nodes (proxy for monitoring device in the current context) (Reddy et al, 2006). Given the context of signal transmission for patient monitoring based on multi-hop MANET, end to end power consumption is utilized as one of the performance measures assessing the applicability of specific PRD protocols for diverse patient monitoring scenarios. The end to end power consumed is manifested in terms of the sum of the transmitted power at each hop in end to end signals transmission.

In the current context battery power of the monitoring device is significant to supporting comprehensive patient monitoring solutions specifically due to the following:

- The monitoring device performs one of the most significant functionalities within the context of the current research i.e. routing and transmitting of alert messages to a healthcare professional. Transmission and routing is critical to provisioning of pertinent medical intervention as and when needed, prevention of crisis, and unnecessary hospitalizations.

- Moreover, reliable end to end signal transmission (i.e. end to end probability of a device/node to locate and transmit a signal to the next node till the signal reaches the destination) is also critically dependent on the battery power of the devices/nodes involved in signal transmission via a multi-hop MANET (i.e. the source device, the intermediate routing devices, and the destination device). The amount of power transmitted influences both the ability of a patient to transmit emergency signals, as well as the end-to-end routing of these signals via multiple hops. The power limitations of co-operative devices will negatively affect their ability to locate next-hops for continued routing.

- Additionally, an end to end delay is also largely dependent on the transmitted power. End to end delay is a function of end to end hops which in turn is dependent on transmitted power.

The battery power of the monitoring *device* impacts the transmitted power level which in turn determines the device range and the number of hops from the source to the

recipient (see Figure 9). The device range of the monitoring device determines the range across which a signal can be coherently received and is therefore crucial in determining network performance in terms of end to end reliability, end to end delay, and end to end power consumption (Krunz, M. et al. 2004). Maximizing reliability implies increasing the device range and decreasing the number of end to end hops between the source and destination thereby requiring an increased level of power consumption for diverse levels of device density. Optimizing power usage requires conserving power by reducing device range and increasing the number of hops between the source and the destination while maintaining an acceptable level of reliability at any given level of device density.

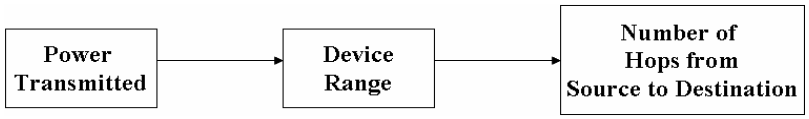


Figure 9: Transmitted Power Impacts Device Range and Number of Hops

Halving the transmission range increases the number of hops by two but decreases the area of the reserved floor to one fourth of the original value, thus allowing for more concurrent transmissions to take place in the same neighborhood (Krunz et al, 2004). Figure 10a and 10b show the impact of the power transmitted by a device "C" on the corresponding transmission range, and the level of interference caused at other devices (i.e. "B"). Optimizing transmission power by device "C" while transmitting signal to device "D", not only reduces power consumption and transmission range of device "C" but also the level of interference caused at device "B" thereby allowing concurrent transmission to take place between "A-B" and "C-D".

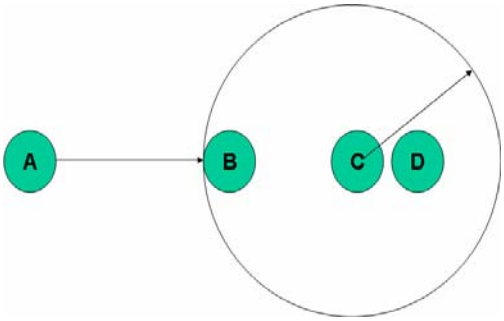


Figure 10a: Transmission from C to D at Higher Power *Causes* Interference at B

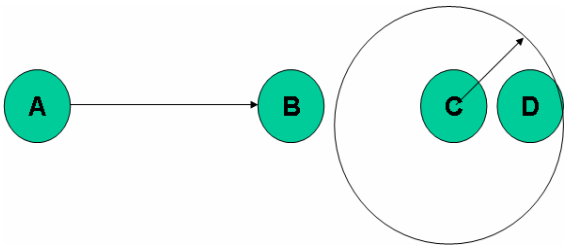


Figure 10b: Transmission from C to D at Lower Power *Reduces* Interference at B

The transmitted power can be less than, greater than, or equal to the minimum power such that the range of the transmitted signal falls within the range of the next node. On one hand, transmitting at a lower power level conserves battery power and reduces device range but it causes an adverse impact on network connectivity. Network partitioning due to nodes falling out of the transmission range leads to low reliability of end to end transmission. On the other hand, transmitting at higher power level increases device range and increases the probability of locating one/more node(s) for further transmission but it causes an adverse impact on efficient power usage. Although transmission at higher power level by nodes can lead to short term increase in reliability but in the longer term excessive power usage causes death of the nodes, network partitioning and thus decrease in end to end reliability. Thus optimal power usage is essential to increasing a device's battery life thereby maintaining the connectivity of the network, increasing time before the network partitions, enhancing end to end reliability of transmission, reducing interference, and increasing throughput.

Notwithstanding is the fact that reduction in the range of transmitted signal by disproportionate reduction in the transmitted power level can negatively impact the probability of the transmitted signal to reach a neighboring device thereby adversely impacting reliable end to end signal transmission and network connectivity. Hence the efficiency in utilization of battery power without sacrificing reliability is of critical importance. An ideal solution will optimize power usage and spatial reuse while ensuring reliability of end to end transmission (Vaidya, 2001).

Recently, power control in mobile ad hoc networks has been the focus of extensive research. A discussion of the tradeoffs involved in selecting the power level is presented by Krunz et al. (2004). Network layer routing solutions with focus on energy consumption with throughput being a secondary factor is presented by Singh et al. (1998) and Gomez et al. (2003). These approaches reduce energy consumption at the expense of decrease in network throughput and increase in delay. Power control schemes that consider the MAC (Medium Access Control) perspective include research focusing on power control algorithms for network topology control (Rodoplu et al. 1999), interference aware power control schemes that use broadcasted interference information to bound the power levels of subsequent transmission (Wattenhofer et al 2001). Other protocols based on cluster heads acting as base stations (Kwon et al. 1999) and a combination of clustering and power control protocol (Kawadia et al. 2003) are also presented. Power control with focus on minimizing power usage in presence of a radio model includes: algorithm for minimum energy paths (Rodoplu et al. 1999), minimizing maximum power level of a node to ensure k disjoint paths between any 2 nodes (Ramanathan et al. 2000). Heuristic based power minimizing approaches in absence of a radio model includes: LINT (Local Information No Topology Protocol, no connectivity gurantees) and LILT (Requires Information from Routing Layer), COMPOW (uniformly

distributed nodes, network Layer), and CLUSTERPOW (non-uniformly distributed nodes). Although the impact of power control on reliability has been discussed in prior research, it hasn't been fully explored and validated. Additionally power usage has not been approached from the perspective of reliability and delays as performance criteria. The current research is novel in the aspect that it has designed and evaluated the impact of power management of the monitoring devices on reliability, delays, and power usage in the specific context of end to end signal transmission for diverse patient monitoring scenarios.

TO SUMMARIZE…….

It is evident from the foregoing discussion that the issue of reliability in ad hoc wireless networks has been addressed by prior researches via multiple approaches including broadcast based schemes and routing protocols to ensure successful signal transmission from the source to destination. Hop by hop acknowledgement, increased power transmission, use of multiple networks have also been suggested. Power control has been researched from the perspectives of network and MAC layer and various solutions have been proposed such as: routing protocols, topology control algorithms, interference aware power control schemes, cluster heads as communication gateway. None of the foregoing researches have fully modeled and evaluated the mechanics and effects of variable-rate support in transmitted power level (Krunz et al, 2004). Reducing the energy consumed by unintended receivers is another aspect of interest that hasn't been entirely explored by prior researches (Vaidya, Open Issues). Power management, reliability, and delay haven't been concurrently addressed and evaluated within the context of a specific application. As different applications have different requirements, the services required by them and the function of the associated key parameters can vary significantly (Reddy et al, 2006). For instance: military applications

might designate security in transmissions as the most critical parameter, and communication at a conference might require that the nodes transmit among each other by using as minimum energy as possible. Hence it is important to conduct context specific research assessing the applicability of multi-hop MANET and the performance of the associated key parameters (Reddy et al, 2006), (Vaidya, 2005). The current research seeks to incorporate efficient power management techniques with respect to signal transmission in diverse patient monitoring scenarios with the goal to maximize reliability at minimal power consumption and delays in end to end signal transmission. It is to be noted that the current research makes no claims that the proposed PRD protocols are better than the existing power control mechanisms. The research simply asserts the utility of the proposed PRD protocols in achieving the desired objectives under diverse monitoring scenarios. Besides none of the prior A comparison of the proposed PRD protocol

CHAPTER 4

POWER, RELIABIITY, AND DELAY (PRD):

PRD PROTOCOLS, SLEEP STRATEGY, AND PM-PRD SCHEME

In Chapter 1, a typical usage scenario utilizing multi-hop MANET was developed. The usage scenario laid the foundation for shaping the specific research question, focus, and objectives for dependable patient monitoring solutions (as discussed in Chapter 1). This chapter presents details of the power management techniques and the corresponding scheme that seeks to optimize resource usage (i.e. battery power) and enhance reliability of end to end signal transmission at reasonable delays in the process of end to end signal transmission via cooperative routers in a MANET. The proposed scheme achieves the desirable objective by incorporating the power management techniques in signal transmission from the source to the destination under diverse patient monitoring scenarios. The artifacts developed and explicated in this chapter are the following:

- *Techniques for power management of the monitoring devices*:

  1. Power-Reliability-Delay (PRD) Protocols operationalizing variable rate power transmissions by the source and intermediate PMDs to enhance reliability. Power consumption and delays in end to end signal transmission varies for each protocol.

  2. Sleep Strategy operationalizing sleep mode to conserve battery power of individual PMDs. The key consideration in incorporating sleep strategy is the impact on overall device density in the area of transmission.

- *PM-PRD scheme* incorporating power management techniques in the process of end to end signal transmission under diverse patient monitoring scenarios to optimize power usage, and enhance reliability at reasonable delays.

The following sections elaborate on: (a) the techniques for power management – PRD protocols and sleep strategy, and (b) the PM-PRD scheme.

POWER MANAGEMENT TECHNIQUES

Efficient context specific, power management strategies are required for optimal utilization of limited battery power of the patient monitoring devices (PMDs) forming a multi-hop MANET. The current research focuses on optimal resource (battery power) utilization as a means to enhance reliability at reasonable delays. The biggest challenge in devising strategies to efficiently utilize battery power in end to end signal transmission is associated with the conflicting goal of optimizing power usage of the PMDs and enhancing reliability at minimal possible delays.

A state model of a typical patient monitoring device (see figure 11) depicts an overview of the logical structure and the functional states consisting of: (a) Monitoring and Processing, (b) Transmitting, and (c) Idle Listening. The state model is leveraged to define the research focus in the context of power management. The PMD depicted in the state model is assumed to perform periodic monitoring of vital signs and alert based transmissions (i.e. signals are transmitted only when an anomaly is detected).

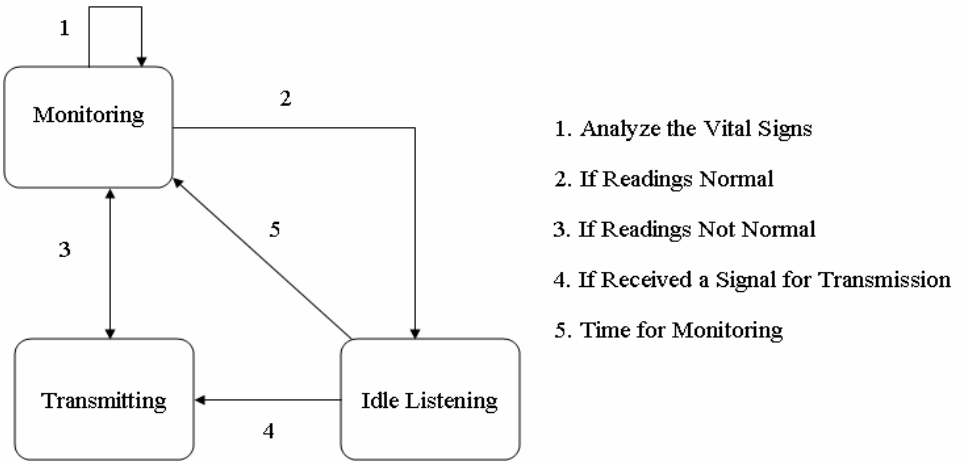


Figure 11: Monitoring Device's State Model

According to the state model, a patient monitoring device can be in any one of the three states at a given point in time. In the monitoring state the device obtaints the vital signs from the sensors and other biometric devices that sense multiparametric data. If an anomaly is detected then it goes to the Transmit State and begins to transmit the alert via multi-hop ad hoc wireless network (assuming the network coverage from infrastructure oriented wired/wireless networks is limited or non-existent). When the PMD is not in the monitoring state and transmission of signal is not warranted the PMD goes to the state of Idle Listening for transmitted signals. Listening to signals consumes significant power but is essential for end to end signal transmission via intermediate PMDs in a multi-hop MANET. If the PMD hears a signal requiring further transmission it goes to the Transmit State.

A monitoring device consumes substantial amount of battery power in transmitting, and idle listening. Power consumed in monitoring the vital signs is outside the scope of the current research because of two key reasons: (a) monitoring or sensing of vital signs is typically done by the sensors and other biometric devices responsible for monitoring multi-

parametric vital signs, and (b)the patient monitoring device merely collects the vital signs via short range wireless transmissions and transmits data as pre-specified in the application. The proposed power management techniques specifically focus on power management at the Transmit and Idle Listening states. An overview of approximate power consumed by a PMD in the various functional states and the scope of the current research with respect to power management are depicted in Figure 12. The research objective in the context of power management is to devise techniques for optimal power usage of the PMD at Transmit and Idle Listening states while considering the complex relationships and dependencies with reliability, delays, and power consumption in end to end signal transmission via a MANET.

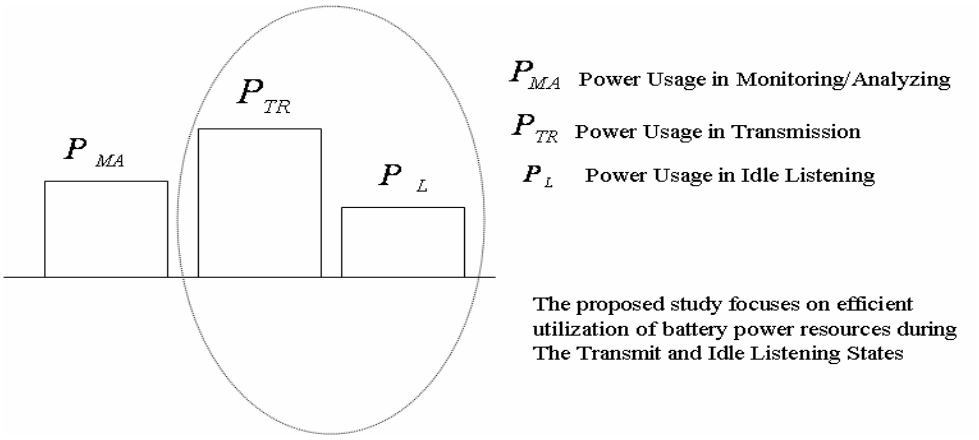


Figure 12: Research Scope in Terms of Power Usage by a PMD

POWER-RELIABILITY-DELAY (PRD) PROTOCOLS

Power-Reliability-Delay (PRD) Protocols seek to manage the battery power of the source and the intermediate PMDs at the "*Transmit State*". The protocols are based on signal

transmissions utilizing variable-rate transmit power by the PMDs. The desirable goal of end to end signal transmission via the proposed PRD protocols is to enhance/maximize reliability under diverse patient monitoring scenarios. End to end power consumption and the corresponding end to end delay is anticipated to vary for different protocols. The performance of the PRD protocols is analytically modeled and evaluated to assess their effectiveness in maximizing end to end reliability. Table 3 summarizes the basic structure of the PRD protocols in terms of the transmitted power levels by the source and intermediate PMDs in end to end signal transmission via a multi-hop MANET. The key metrics used in evaluating the performance of the PRD protocols and the corresponding applicability to diverse patient monitoring scenarios are: end to end power consumption, end to end reliability, and end to end delays in signal transmission.

It is to be noted that the current research makes no claims that the proposed PRD protocols are *better* than the existing power control mechanisms. Whereas, prior research in power management reveals heuristic mechanisms, algorithms, and protocols designed specifically to minimize power consumption the unique contribution of the PRD protocols lies in its objective to maximize end to end reliability in signal transmission for diverse monitoring scenarios. The research simply asserts the utility of the proposed PRD protocols in achieving the desired objectives under diverse monitoring scenarios. The corresponding results (in chapter 6) establish the feasibility of leveraging MANETs for achieving dependable patient monitoring applications.

Table 3: Overview of the Protocols for Power Management

Nodes	Protocol 1	Protocol 2	Protocol 3	Protocol 4
Patient's Device	Transmit Power Level - Random	Transmit Power Level - Maximum	Transmit Power Level - Maximum	Transmit Power Level - Optimum
Intermediate Routing Devices	Transmit Power Level - Random	Transmit Power Level - Maximum	Transmit Power Level - Optimum	Transmit Power Level - Optimum

The basic assumption with respect to the PRD protocols is that the PMDs (source and the intermediate PMDs) involved in patient monitoring via a multi-hop MANET are capable of transmitting signals at variable-rates. The protocols support broadcast routing schemes; and various patient monitoring requirements such as: reliability, mobility, and transmissions (alert, continuous, and periodic). Operationalizing the PRD protocols entails signal transmission from the source to the destination via intermediate PMDs. The source is defined as the PMD initiating transmission. The destination is a healthcare professional's device. The intermediate PMDs are the cooperative devices that can hear and route the transmitted signal further. The signal can be transmitted from the source to the destination via (a) a pure multi-hop MANET or (b) a multi-hop MANET in conjunction with infrastructure based network that intercepts the signal and tunnels it via the infrastructure to the destination. Signal transmission via the PRD protocols is applicable only for a MANET. Signal intercepted and transmitted via an infrastructure based network will follow the specific protocols supporting transmissions via the infrastructure based network. Figure 13 depicts the impact of PRD protocols manifested either directly or indirectly on end to end power consumption, end to end reliability, and end to end delays.

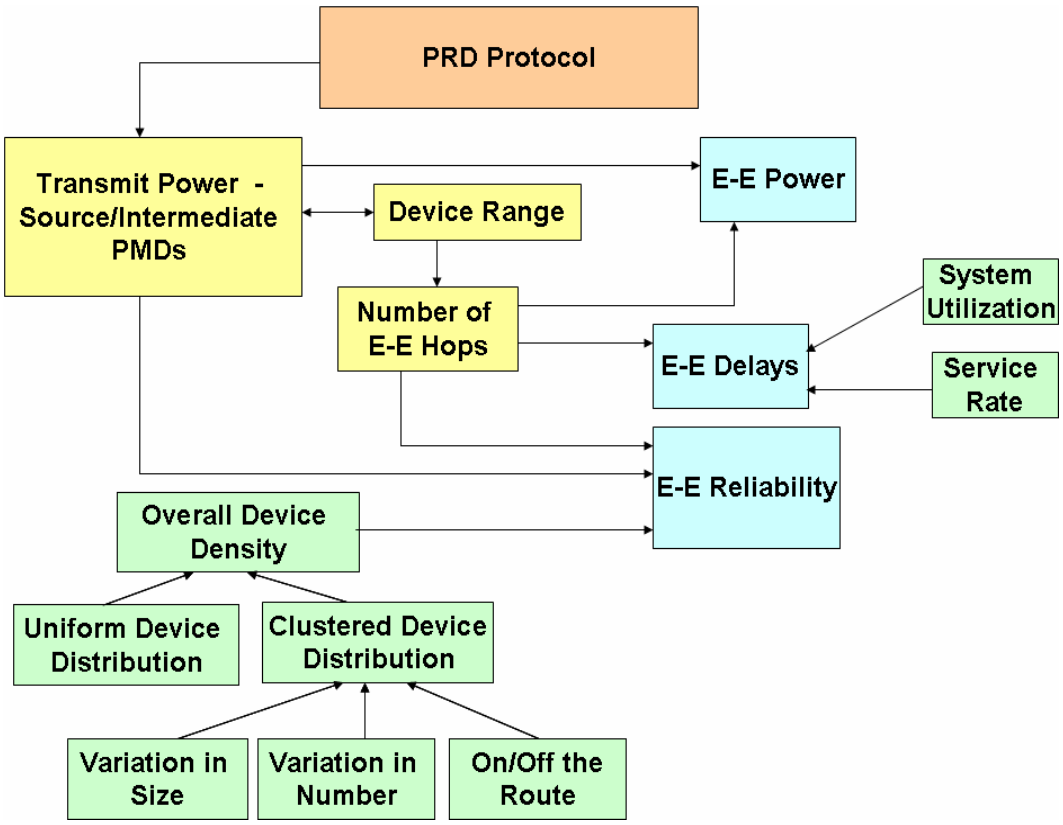


Figure 13: Impact of PRD Protocols on E-E Power, E-E Reliability, and E-E Delays

1. Random from Patients and Random from Cooperative Devices (RP-RCD):

The protocol RP-RCD requires the patient and the intermediate PMDs to transmit the signal at a random power level till the signal reaches the destination. In this case end to end signal transmission takes place via a random power level at each consecutive hop. For example if a device can transmit signals at three power levels: Min, Med, and Max and the device are transmitting according to RP-RCD then for each transmission the PMD randomly selects a power level. The power level at which transmission takes place also depends on the available power budget of the transmitting PMD. For example if the power level randomly

selected is Max and the device doesn't have enough power to transmit at the Max level then the device will transmit at the next lower power level. Figure 14 depicts two typical transmissions via RP-RCD. The end to end signal transmission can take place from A-B-C-D (4 hops) or A-E-D (3 hops).

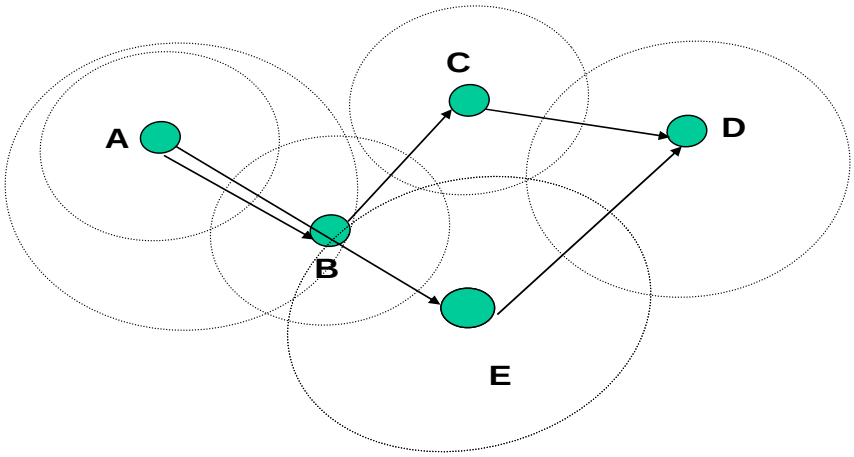


Figure 14: End to End Transmissions via RP-RCD

The advantage of RP-RCD is less processing by the PMD in selecting a transmission power level. RP-RCD can potentially lead to variable power level each time a signal is transmitted and can thereby result in variable reliability and delays in end to end signal transmission. Inefficient power consumption can be another disadvantage of using RP-RCD. If a certain transmission using RP-RCD randomly selects a power level equivalent to Max, then it can potentially lead to inefficient usages of the battery power if a Min/Med power level was required to transmit the signal to the next closest PMD. For example: In the route A-E-D (see Figure X) power usage is inefficient since transmission takes place at a higher power level than the minimum required to reach the nearest node. Since the transmitted power varies

each time a transmission takes place hence it is difficult to accurately predict the performance of the RP-RCD protocol with respect to end to end power consumption, end to end reliability, and end to end delays for a given patient monitoring scenario.

2. Maximum from Patients and Maximum from Cooperative Devices (MP-MCD):

The protocol MP-MCD requires the source and the intermediate PMDs to transmit the signal at maximum power level till the message reaches the destination. Transmission via MP-MCD can result in equal transmission range at each hop in end to end signal transmission in case the PMDs are symmetrical with respect to battery power (i.e. transmission power level for each PMD is equal thereby resulting in equal device range in end to end hops). In case the nodes are asymmetrical, the maximum power level at each node will vary and so will the transmission range of each node. Figure 15 shows a typical transmission via MP-MCD.

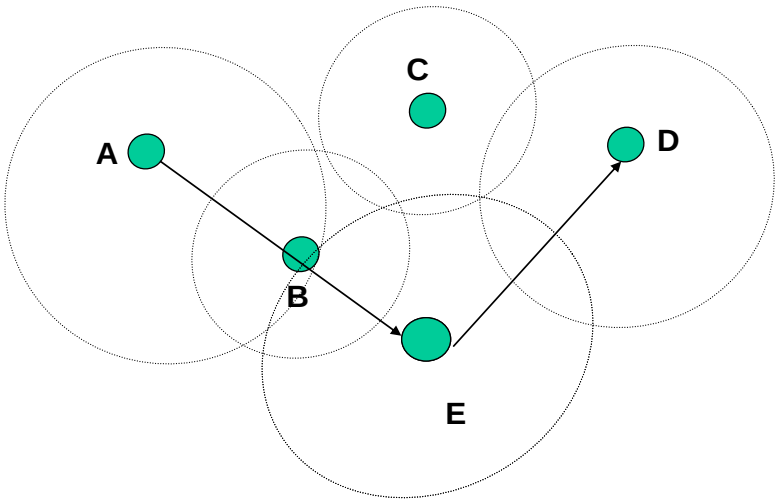


Figure 15: End to End Transmissions via MP-MCD

The protocol is simple since it does not involve any processing, does not need to keep track of power levels, and is also less sensitive to patient mobility as the transmitted power is always kept at the maximum level irrespective of the levels of patient/device density in the area. MP-MCD leads to increased transmission range, and decreases the number of hops involved in routing the messages. Fewer intermediate hops reduces delays and increased device range leads to higher probability of locating cooperative PMDs for further signal transmission thereby leading to high reliability in message delivery. MP-MCD significantly increases the probability of finding a cooperative PMD for continued routing even when the device density is relatively low. The disadvantage of MP-MCD is associated with inefficient power usage, especially in areas of high device density. For example: end to end signal transmission via MP-MCD across A-E-D results in higher power consumption, reliability, and lower delays (see Figure 15).

MP-MCD is suitable for the delivery of emergency messages, and especially performs well under low device density, when higher transmitted power is required to locate a cooperative PMD. Only in some extreme cases of very scanty patient/device density, MP-MCD may not find a neighboring PMD for continued signal transmission. The characteristics of MP-MCD for signal transmissions are as follows:

(a) Maximum level of transmitted power results in maximum possible device range in signal transmission from source to destination which in turn results in minimum number of end to end hops. Minimal number of hops from the source to destination results in minimal delays in end to end signal transmission for a given patient monitoring scenario.

(b) Maximum level of transmitted power leads to higher end to end reliability in signal transmission due to higher probability associated with the transmitted signal to reach a cooperative device.

(c) Least processing required since each device transmits signal at the maximum power level.

(d) Potentially inefficient usage of battery power (especially in areas with high device density).

(e) High interference level causing constraints in concurrent transmissions.

3. Maximum from Patients and Optimum from Cooperative Devices (MP-OCD):

The protocol MP-OCD requires the source to transmit at the maximum power level while the intermediate PMDs transmit signal at the optimal power level till the message reaches the destination (see Figure 16). Optimal power level is defined as the minimum power at which the transmitted signal from a PMD reaches the nearest cooperative PMD for further signal transmission. Optimal power level is approximated by a PMD based on the power level of the prior transmissions of the neighboring PMDs. Assuming a PMD has three power levels at which it can transmit signal (i.e. Min, Med, and Max) then the optimal power level (OP) is such that Min <= OP <= Max.

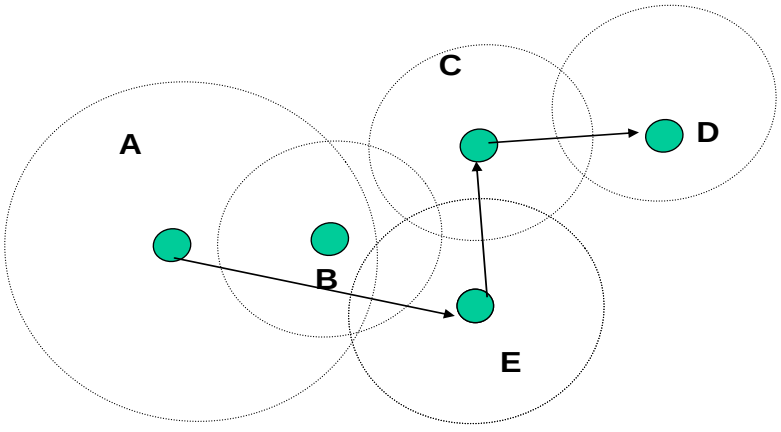


Figure 16: End to End Transmission via MP-OCD

The critical advantage of MP-OCD is efficient power consumption by the intermediate PMDs while ensuring reliability at reasonable delays in end to end signal transmission. In addition to power conservation, this protocol can be considered as the fairest protocol since the source transmits at a higher power level than the intermediary PMDs. The processing load for computing the optimal power level however is associated only with the intermediate PMDs, not with the source since the source always transmits at the maximum power level. In some instances, of low device density, MP-OCD may be preferred over OP-OCD since optimal power level may potentially be equal to the Max power level. Thus selecting MP-OCD may result in saving processing time and power. MP-OCD also has reduced delays than OP-OCD and is applicable for situations involving non-emergency and periodic transmission of routine vital signs. End to end signal transmission via MP-OCD has the following characteristics:

(a) relatively more processing required in detecting the optimal power level for signal transmission by the intermediate routing nodes. However it is efficient than RP-RCD and MP-MCD with respect to efficiency in transmit power consumption.

(b) allows for lower interference level than both RP-RCD and MP-MCD thus allowing more concurrent transmissions to take place in a given transmission area.

(c) ensures end to end reliability to be consistently high

(d) relatively more hops in end to end route than RP-RCD and MP-MCD. This could potentially result in relatively higher end to end delays than RP-RCD and MP-MCD.

4. Optimum from Patients and Optimum from Cooperative Devices (OP-OCD):

The protocol OP-OCD requires the source and the intermediate PMDs to transmit signal at the optimal power level till the signal reaches the destination. Optimal power level is

approximated based on the power level of the prior transmissions of the neighboring PMDs. Figure 17 depicts signal transmission via a multi-hop MANET using OP-OCD.

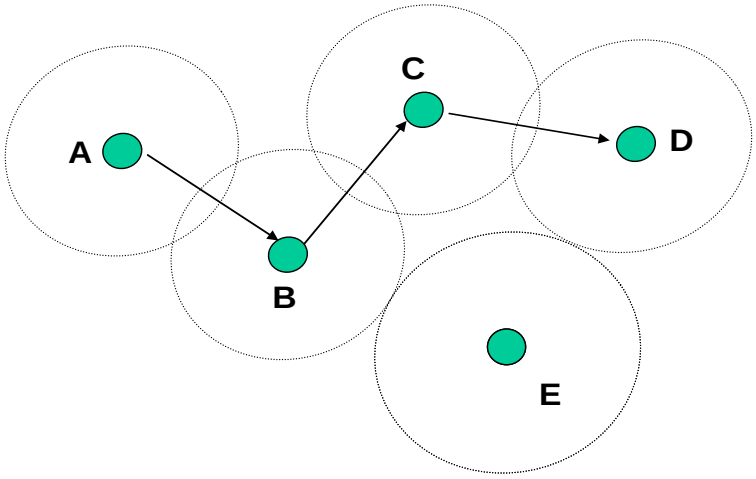


Figure 17: End to End Transmission via OP-OCD

OP-OCD seeks to optimize the power levels of all the PMDs involved in transmitting the signal, resulting in the highest level of power efficiency. The tradeoff is potentially a longer end to end route with multiple hops, increased delay due to higher number of end to end hops. The complexity of the protocol results from the overheads of associated with deriving optimal power levels, which may require a processing of prior transmissions/receptions to estimate the optimal power necessary to reach the next node. OP-OCD is suitable in areas with high device density where the optimal power level stays within close proximity to the *Min* power level where the probability of locating the next node is 100%. Under more scattered devices or low device density, OP-OCD may not work well, since the overheads of the computations for deriving the optimal power level of transmission might overweight the benefits of power conservation. The worst instance is when the low density causes the optimal power level to be equal to the maximum power level thereby completely nullifying the objective of power conservation. The mobility of nodes may also affect the optimal power

levels. OP-OCD is suitable for non-emergency, periodic transmission of routine vital signs from a patient's device to healthcare professionals or for emergency transmissions in areas of high device density. End to end signal transmission via OP-OCD has the following characteristics:

(a) relatively more processing required in detecting the optimal power level for signal transmission by the source and the intermediate routing nodes. However OP-OCD is the most efficient with respect to efficiency in transmit power consumption than all the other preceding protocols (i.e. RP-RCD and MP-MCD, MP-OCD).

(b) allows for lowest interference level than all the other preceding protocols (i.e. RP-RCD and MP-MCD, MP-OCD) thus allowing more concurrent transmissions to take place in a given transmission area.

(c) ensures end to end reliability to be consistently high

(d) potentially more hops in end to end route than all the other preceding protocols (i.e. RP-RCD and MP-MCD, MP-OCD). This could potentially result in relatively higher end to end delays than RP-RCD, MP-MCD, and MP-OCD.

A comparison of the proposed PRD protocols with respect to the key evaluation metrics, applicability to diverse patient monitoring scenarios, and the processing requirements is presented in Table 4.

Table 4: Comparative Assessment of the PRD Protocols.

Protocol	End to End Reliability	End to End Power Usage	End to End Delays	Processing Requirements
MP-MCD	High – even in areas of low device density	Highest - Battery may not last long if MP-MCD is always utilized	Lowest - due to minimal end to end hops	None - PMDs transmit at maximum power levels
OP-OCD	High - especially for low device mobility	Lowest – Highest power efficiency	Highest - due to maximum end to end hops	Very high - determining optimal power levels at each hop
MP-OCD	High	Less Power Usage than MP-MCD but More than OP-OCD	More than MP-MCD but Less than OP-OCD	High -determining optimal power levels for most PMDs
RP-RCD	Unpredictable - based on the power level of individual hops	Unpredictable - based on the sum of all transmitted power levels	Unpredictable - based on the number of end to end hops	Low - all PMDs still have to select a random transmission power level

SLEEP STRATEGY: POWER MANAGEMENT AT IDLE STATE

Sleep strategy focuses on power conservation of the individual patient monitoring devices by allowing them to transition to sleep mode. A PMD consumes substantial amount of power during Idle State (Vaidya, 2006). Table 5 gives a representation of power consumed by a node at transmit, idle, and sleep states. The power consumed at Sleep state is significantly lower than power consumed at Idle State, thus motivating the employment of sleep strategy to reduce power consumption during Idle state.

Table 5: Power Characteristics during Various Radio States

Radio State	Power Consumption (mW)
Transmit	81
Receive/Idle	30
Sleep	0.003

(Adapted from Vaidya, 2006)

Employing sleep strategy for power conservation at Idle state refers to transitioning of PMDs to sleep mode. The PMDs in sleep mode conserve battery power because a "sleeping" device does not participate in: (a) sensing/analyzing patient's vital signs, (b) listening to transmissions from neighboring nodes, and (c) transmitting signals via a multi-hop MANET in end to end routing. The key consequences of PMDs transitioning to sleep mode are: (a) conservation of battery power of the individual devices and (b) a reduction in device density in the area of transmission.

Sleep mode significantly reduces power consumption of the individual PMDs in idle listening thereby increasing the time before a PMD runs out of available power. The detriment is associated with the fact that sleep strategy negatively impacts the density of devices capable of listening and transmitting a signal in the area of transmission. Device density in the area of transmission plays a significant role in reliable end to end signal transmission. Since signal routing/transmission in a multi-hop MANET chiefly depends on the availability of devices/nodes capable of routing a signal hence the primary consideration made in the current context towards leveraging sleep strategy is associated with device density in the area of transmission. A disproportionate number of devices transitioning to sleep mode can have a negative impact on device density in the area of transmission potentially leading to network partitioning and adversely impacting end to end reliability in signal transmission.

Thus the complexity of employing sleep strategy is associated with finding the balance where energy conservation due to PMDs transitioning to sleep mode does not have an adverse impact on network connectivity and reliability of signal transmission via multi-hop MANET.

On one hand, transitioning to sleep mode causes a reduction in the number of devices capable of routing signal in the area of transmission thereby negatively impacting network density or device density in the area of transmission. But on the other hand it results in saving battery power of the individual devices in the sleep mode and can potentially extend the life of the network. The research objective with respect to the applicability of sleep strategy for diverse patient monitoring scenarios is associated with finding the threshold device density above which sleep strategy can be applied without adversely impacting reliability of end to end signal transmission in the context of patient monitoring. In the current research the impact/applicability of sleep strategy is analytically modeled chiefly in terms of device density in the area of transmission. Hence the goal with respect to the applicability of sleep strategy is to investigate the best density zones where sleep strategy can be utilized without adversely impacting reliability. The utility of sleep strategy towards efficient energy utilization is applicable when the network traffic is low and delay constraints are not rigid, and in areas of high device density where signal routing is not adversely impacted by a few nodes going in the sleep mode.

There are two possible design alternatives for sleep strategy, a scheme based on coordinators and non-coordinators who function synchronously, i.e., timer-based or a scheme based exclusively on non-coordinators. There might be asymmetry in the capacity of the routing nodes such that the coordinators are nodes with higher capabilities in

routing/processing and battery power while the non-coordinators are nodes with relatively lower processing capabilities and battery power.

A scheme based on coordinators and non-coordinators who function synchronously, i.e., timer-based. A sleep strategy based on coordinators and non-coordinators assumes that there might be asymmetry in the capacity of the routing nodes such that the coordinators are nodes with higher capabilities in routing/processing and battery power while the non-coordinators are nodes with relatively lower processing capabilities and battery power. The devices that can go to sleep are non-coordinators while the devices that stay awake and forward signals on behalf of the sleeping devices are the coordinators. The coordinators maintain network connectivity while non-coordinators transition to sleep.

A scheme based exclusively on non-coordinators functioning in a synchronous fashion. The nodes in this case transition in/out of sleep mode in a synchronous fashion. This design is suitable for areas where the nodes have limited mobility and/or node density is high. Table 6 presents details of the sleep strategy.

Table 6: Details of Sleep Strategy Alternatives for Power Control at Idle State

Design Alternatives	Node Functionalities	Comments
Sleep Strategy Based Only on Non-Coordinator Nodes **- Nodes with relatively lower battery power and processing capabilities.**	Functions in a synchronous manner, i.e., wakes up and goes to sleep at a pre-specified time interval (timer based). The sleep cycle will coincide with the periodic monitoring cycle of the device. If an anomaly is detected and transmission warranted by the monitoring device, then the device begins transmission and transition to the sleep mode is not made. Sleep strategy can be triggered later when	The advantage is that all the processing is local to the node itself. Less network traffic due to communication between the coordinator/non-coordinator nodes. The disadvantage is that there is no backup in case where the route to the destination goes through the sleeping node.

	the device resumes the normal monitoring cycle.	
Sleep Strategy Based on Non-Coordinator Nodes in Conjunction with Coordinator Nodes **- Nodes with higher battery power and processing capabilities**	The neighboring non-coordinator nodes register with the coordinator node. The coordinator node manages which nodes go to sleep mode by communicating with the non-coordinator nodes. The sleep mode is synchronous for the non-coordinator nodes (as discussed above). If the node detects an anomaly, it can override the coordinator's signal to go to sleep and begin transmission.	The advantage is that coordinators can route the signals for the non-coordinators when the latter is in the sleep mode. The disadvantage is increased network traffic. Mobility of nodes causes complexity in keeping track of coordinators/non-coordinators.

Figure 18 graphically depicts a sleep strategy based on the use of coordinators and non-coordinator nodes. In Figure 18, device A determines and informs devices S1 and S2 on their power setting based on the level of emergency traffic and device density. As device B notices high device density it informs S4 and S6 to go through sleep cycle and S3 and S5 to go into lower power mode. As device C observes only S7 and S8 in its range, it offers no sleep cycle, but assists these devices in their power management.

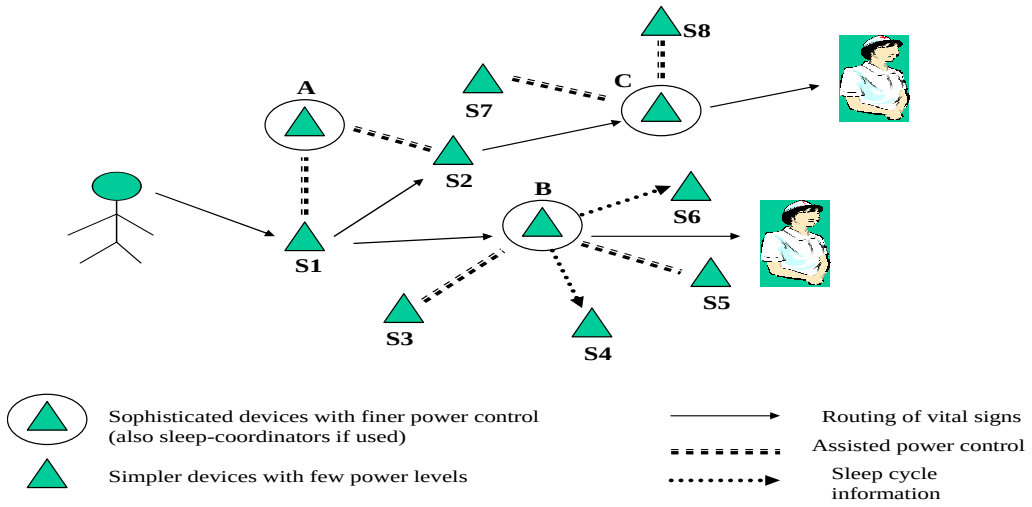


Figure 18: Assisted Power Management and Sleep Strategy

The factors that need to be considered for the applicability of sleep strategy in a patient monitoring scenario include: current levels and recent changes in vital signs, maximizing energy conservation by allowing maximum possible devices to sleep while maintaining network connectivity, fairness of sleep times for devices, energy conservation, overhead of sleep strategy, and mobility levels of patients. For example:

- Device of a patient, whose vital signs have gone above/below a certain critical threshold in the previous readings, should not go in the sleep cycle (or at least postpone until the rate of change for vital signs reduces and/or vital signs return to normal range).
- Devices of patients with little or no mobility can have longer sleep durations, especially if there are many other patients/devices in range to route signals.

In the current context, sleep strategy is triggered by the PM-PRD scheme after analyzing its applicability for a given patient monitoring scenario.

PATIENT MONITORING-POWER-RELIABILITY-DELAY (PM-PRD) SCHEME

A scheme that incorporates PRD protocols and/or sleep strategy in the process of end to end signal transmission is developed and expounded in this section. The significance of the PM-PRD scheme comes from its contributions in operationalizing an appropriate power management technique (PRD protocol and/or sleep strategy) in the process of end to end signal transmission such that not only the requirements/constraints of patient monitoring scenarios are met but also the desirable goal of optimizing end to end power consumption, enhancing end to end reliability, at acceptable level of end to end delays is achieved.

The proposed PM-PRD scheme consists of three key processes (see Figure 19): (a) analyzing a patient monitoring scenario as characterized by its attributes, (b) assessing the key constraints/requirements, and (c) operationalizing appropriate power management technique(s) (i.e., PRD protocol and/or sleep strategy) in the process of end to end signal transmission that best meets the requirements/constraints of the given patient monitoring context. The details of each process and the key tasks accomplished in the respective process are explained in the following sections. Formal expressions/algorithms of specific tasks associated with the processes in the PM-PRD scheme are presented in Appendix A.

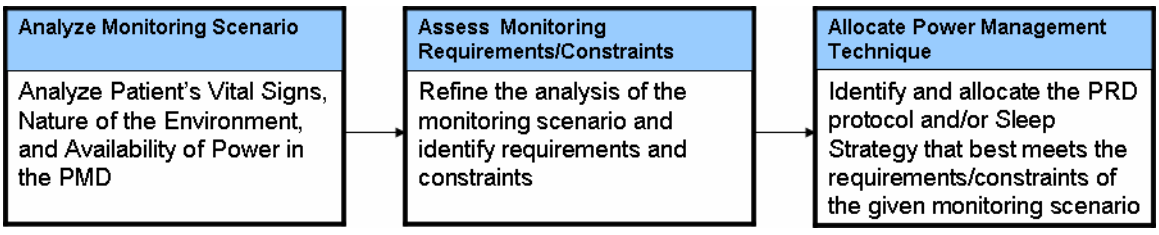


Figure 19: Overview of Key Process Underlying the PM-PRD Scheme

Process 1: Analyzing a Patient Monitoring Scenario

The first process consists of three tasks that incrementally build the context of the specific patient monitoring scenario. The context is built by obtaining relevant information pertaining to the parameters characterizing a patient monitoring scenario in the context of the current research. The parameters defining a patient monitoring scenario in the current research consists of: attributes defining the characteristics of the patient's vital signs, attributes defining the characteristics of the environment, and attributes defining the characteristics of the device such as: the available resource (i.e. battery power). Diverse patient monitoring scenarios are painted by variations in the attributes characterizing the signal, the environment, and the device. Following is a brief over view of the parameters shaping diverse patient monitoring scenarios in the context of the current study:

Attributes Defining the Characteristics of the Signal to be Transmitted:

- *Nature of the Signal (NS*): The patient monitoring device may transmit a signal that can be of high emergency, medium emergency, or low emergency/routine. The nature of transmitted signal influences the power management technique(s) that can be utilized in end to end signal transmission.

Attributes Defining the Characteristics of the Environment:

- *Area of Transmission (AT*): The area in which the patients are monitored for detection of anomalies is used as a determinant of the area in which signal transmission takes place.

- *Number of Patients in the Area of Transmission (NPAT*): The number of patient monitoring devices capable of routing and transmitting a signal in the area of transmission is used to determine the device density in the area of transmission.

- *System Utilization:* The utilization of the system impacts end to end delays. Higher system utilization is anticipated to increase end to end delays and vice-veresa for low system utilization.

- *Mobility of Patients in the Area of Transmission*: The patients can be stationary or mobile in a given area of transmission. Mobility of patients in the area of transmission influences their distribution and the corresponding distribution of the patient monitoring devices. The devices can thus have uniform or clustered distribution (Figure 20).

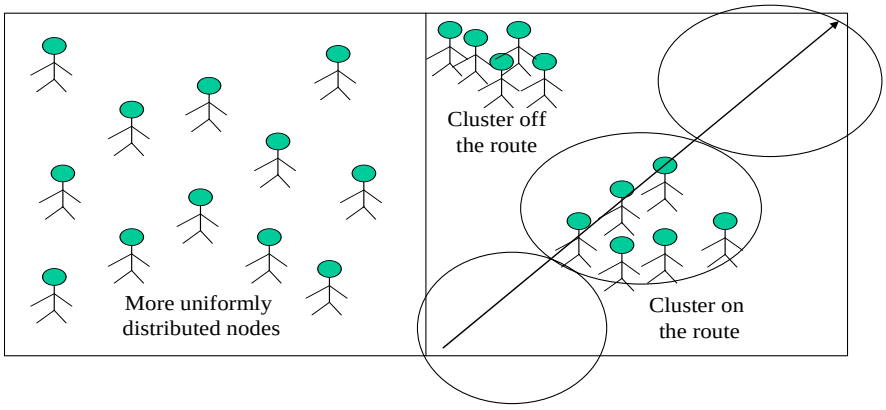


Figure 20: Uniform Distribution versus Clustered Distribution in the Area of Transmission

- *Device Distribution*: Uniform distribution of patients in the area of transmission leads to uniform density of patient monitoring devices capable of transmitting and routing signals via a multi-hop MANET. Clustered distribution of patients in the area of transmission on the other hand leads to clustered density of patient monitoring devices capable of transmitting and routing signals via a multi-hop MANET. Clustered distribution negatively impacts the overall device density in the area of transmission. Moreover the clusters of patient monitoring devices can vary in number, size, and in being on/off the route of signal transmission via a multi-hop MANET. For instance consider the scenario of patients being monitored in a nursing home. These patients will be approximately uniformly distributed in their individual rooms at night or early morning. On the other hand the patients might have clustered distribution during lunch time when they are all clustered together in the lunch room leading to scanty distribution elsewhere in the nursing home. Device distribution affects overall device density in the area of transmission (see Figure 21).

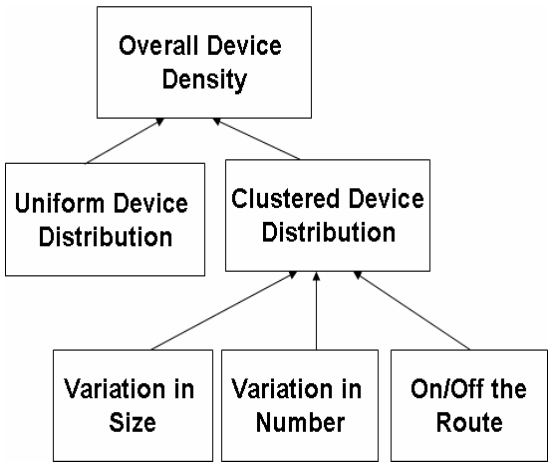


Figure 21: Factors Impacting Overall Device Density in the Area of Transmission

Attributes Defining the Characteristics of the Monitoring Device:

- *Battery Power of the Monitoring Device*: The battery power of the monitoring device is critical to influencing the transmitted power and the quality of services/applications involving the monitoring device in a multi-hop MANET. The battery power of the monitoring device is an important determinant of device range, number of end to end hops in signal transmission.
  - *Device Range*: The power transmitted largely determines the range of the transmitted signal (i.e. device range)
  - *Number of End to End Hops*: The number of hops in end to end signal transmission is a function of the power transmitted at each hop (i.e. device range) and the end to end distance in signal transmission.

Following is a description of the key tasks accomplished in Process 1:

- *Task 1: Analyze Patient's Vital Signs* - The patient's vital signs are obtained and digitized prior to analyzing. The goal of analyzing the vital sign is to detect an anomaly (assuming alert based transmissions) and classify the level of urgency associated with the anomaly. The anomaly can be classified as an emergency or routine.

- *Task 2: Analyze Patient's Environment* - The environment in which end to end transmission takes place is analyzed to approximate the density of PMDs in the area of transmission, the device distribution (i.e. uniform/clustered), the presence/absence of clusters (if any), and the level of system utilization. The device density and distribution is approximated based on hearing to the past signal transmissions. The overall device density (ODD) is characterized as high/low based on a threshold value of device density where high

represents device density being greater than the threshold device density (TDD) and vice versa for low device density. The system utilization is also characterized as high or low compared to a threshold system utilization level (TSU).

- *Task 3: Analyze Patient's Device* – The PMD is analyzed with respect to the availability of resources (i.e. battery power level - BPL). Availability of battery power is assessed in terms of BPL above (i.e. high) or below (i.e. low) the threshold battery power (TBP).

Process 2: Assess Patient Monitoring Requirement/Constraints

Diverse patient monitoring scenarios have diverse constraints/requirements associated with power, reliability, and delays. For instance: routine transmissions can tolerate a higher end to end delay and the focus can be on efficient power utilization and reliability. On the other hand emergency transmissions have minimal delay tolerance, require highest level of reliability even at the cost of efficient resource utilization. In Process 2 the context of patient monitoring is refined in terms of the constraints and requirements of end to end signal transmission via the following tasks.

- *Task 4: Assess the constraints of the patient monitoring context* – The parameters characterizing the constraints of the patient monitoring requirements are obtained from Stage 1 and include: (a) anomaly detected (Yes/No) and/or alert categorized as emergency/routine, (b) overall device density as high/low, and (c) available battery power level as high/low.

- *Task 5: Assess the requirements of the patient monitoring context* - Diverse patient monitoring scenarios assign diverse levels of priority to power management, reliability, and delays in end to end signal transmission. The constraints in the context of patient monitoring (identified in task 4) are utilized to parameterize the respective requirements/priorities associated power management, reliability, and delays in end to end signal transmission (see Table 7). For instance the delay tolerance in end to end transmission is derived based on the level of alert as categorized in terms of Emergency and Routine such that delay tolerance is low for Emergency transmissions and high for Routine. it is assumed that the PMDs have available battery power to transmit signals.

Table 7: Patient Monitoring Scenarios and Relative Priorities Corresponding to Power Management, Delay, and Reliability in End to End Transmission

Application/Scenario	Efficiency in Power Usage	Reliability	Low Delays
A Patient Transmitting an Emergency Signal in an Area of Low Device Density	Lowest Priority	Highest Priority	Highest Priority
A Patient Transmitting Routine Signal in an Area of Low Device Density	Relatively Low Priority	High Priority	Relatively Low Priority.
A Patient Transmitting an Emergency Signal in an Area of High Device Density	Relatively Low Priority	High Priority	High Priority
A Patient Transmitting Routine Signal in an Area of High Device Density	Highest Priority	High Priority	Relatively Lower Priority

Process 3: Allocate Appropriate Power Management Technique

Process 3 incorporates power management techniques that best meets the requirements/constraints of a given patient monitoring scenario with the objective to optimize power usage while enhancing reliability at reasonable delays in end to end signal transmission. Utilizing power management techniques (PRD protocols and/or sleep strategy) without complete assessment of the context of patient monitoring (expressed in terms of the constraints and requirements) could potentially lead to sub-optimal performance with respect to end to end power consumption, end to end reliability, and end to end delays in end to end signal transmission. Neither unnecessary drainage of battery power nor excess conservation of battery power at the cost of reliability and delays are acceptable options in the context of dependable patient monitoring solutions via multi-hop MANET.

- *Task 6: Assess the Applicability of Sleep Strategy* – The constraints of patient monitoring are evaluated to assess the applicability of sleep strategy in the "Idle State". If there is no anomaly detected in the patient's vital signs then the environmental attributes primarily pertaining to the overall device density in the area of transmission are assessed. The goal is to trigger sleep mode such that network connectivity is not adversely impacted hence the primary factor based on which the sleep mode is triggered is the overall device density. If the PMD is in an area of high device density then the sleep mode is triggered for a pre-specified time interval = time the PMD stays in the "Idle State". The device wakes up after the predefined time to continue monitoring and transmitting (if required). The sleep cycle of the PMD is voided if the overall device density falls below the threshold device density or if an anomaly is detected. The sleep strategy can be triggered later by an increase in device density in the area of transmission and/or when the patient's condition is stable again.

The formal expression for invoking sleep strategy is presented in Appendix A.

- *Task 7: Operationalize an Appropriate PRD Protocol for signal transmission* – Based on the analysis of the respective priorities attached to the patient monitoring requirements and constraints an appropriate PRD protocol is operationalized for end to end signal transmission via a multi-hop MANET. The appropriate PRD protocol manages the transmit power of the source and the intermediate routing devices/nodes till the signal reaches the desired destination. The analysis at the intermediate routing nodes is limited to checking the battery power of the node to support the selected power management protocol. If an intermediate routing device lacks sufficient power to support transmission of signal at the specific power level, the node transmits at the next lower power budget available. The transmission from the source consists of the alert message, the address of the destination, and the allocated PRD protocol based on which the intermediate PMDs transmit signal further.

The essence of the PM-PRD scheme is in complementing the PRD protocol. While the PRD protocols enhance reliability in end to end signal transmission at reasonable delays the PM-PRD scheme optimizes resource usage (i.e. battery power). The detailed logical architecture of the PM-PRD scheme is presented in Figure 22. The architecture depicts the the key processes, tasks, and the corresponding decisions criteria with respect to analyzing a given patient montioring scenarios, assessing the corresponding requirements/constraints, and operationalizing the best PRD protocol.

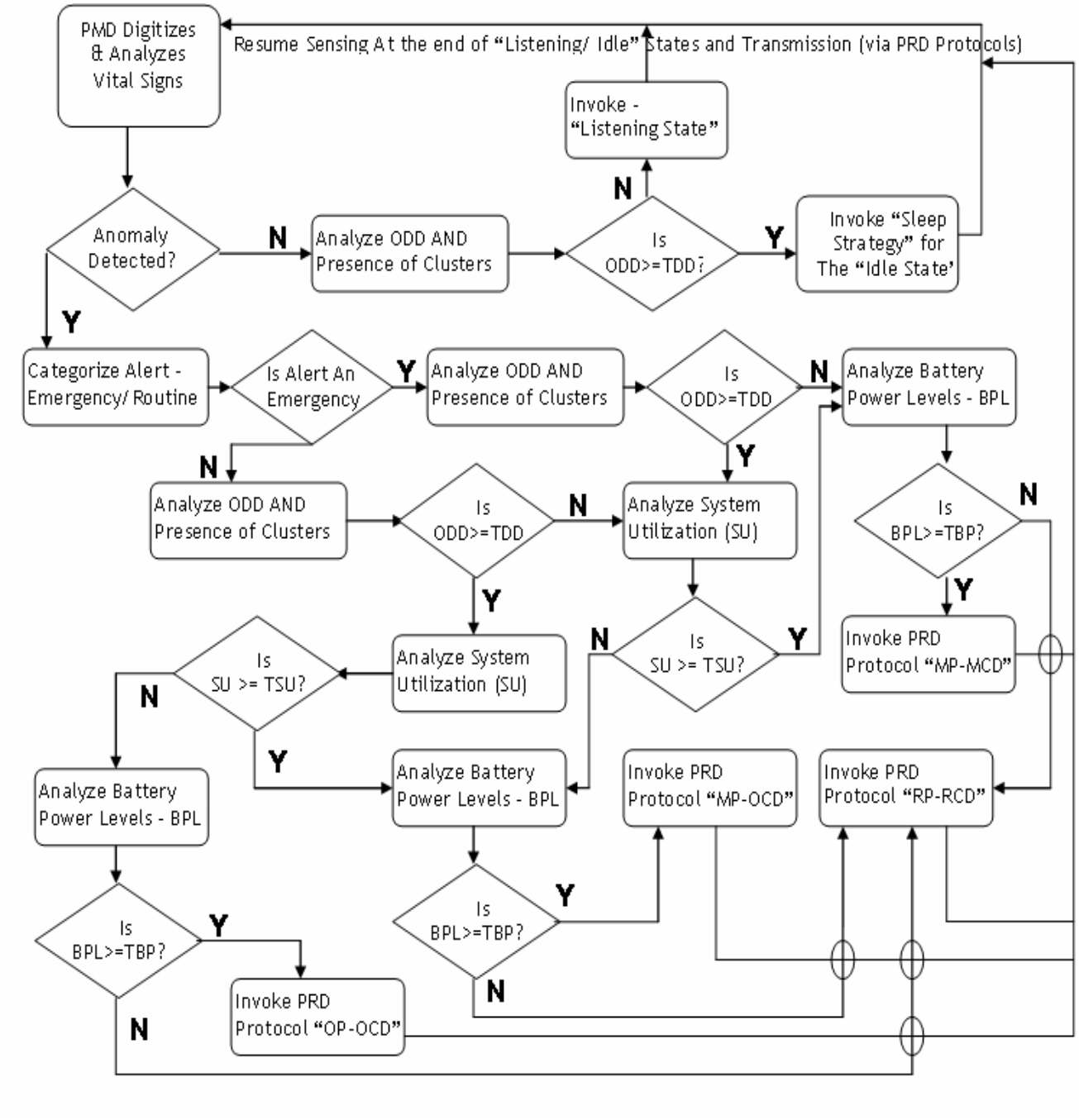


Figure 22: Logical Architecture of the Patient monitoring-power-reliability-delay (PRD) Scheme

Table 8 presents an overview of the PM-PRD scheme in terms of (a) the allocation of PRD protocols, (b) the corresponding requirements associated with reliability and delays in end to end signal transmission, (c) the impact on power usage, and (d) the context of patient monitoring and the constraints expressed in terms of overall device density and classification of vital signs. The PMDs are assumed to have power available to conduct signal transmission via the allocated protocol. For instance: when an emergency vital sign is transmitted in an area of low device density the requirements are to maximize reliability and minimize delays. Thus the PM-PRD scheme operationalizes the MP-MCD protocol for signal transmission since it maximizes reliability at minimal delays at the cost of highest power usage by the source and intermediate routing devices in end to end signal transmission.

Table 8: Operationalizing PRD Protocols in End to End Signal Transmission

	Classification of Transmitted Vital Signs	
Overall Device Density	**Emergency**	**Routine**
High	**MP-OCD** Power Usage: High Reliability: High Delays: Low	**OP-OCD** Power Usage: Lowest Reliability: High Delays: Higher Relative to Other Protocols
Low	**MP-MCD** Power Usage: Highest Relative to Other Protocols Reliability: High Delays: Lowest	**MP-OCD** Power Usage: High Reliability: High Delays: Low

The patient monitoring device (PMD) obtains a patient's vital signs in the analog domain and then digitizes it for further analysis. Once the PMD has performed the functioning of the respective state in which it was as dictated by the PM-PRD scheme (i.e. Listening State, Sleep State, or Transmitting State) it resumes the normal functioning by going back to the state where it senses and analyzes patient's vital signs.

An overview of the conceptual process underlying the proposed PM-PRD scheme is presented in Figure 23. The figure depicts the process of end to end signal transmission via a multi-hop MANET in terms of the processes and tasks accomplished by the source device and the intermediate patient monitoring devices.

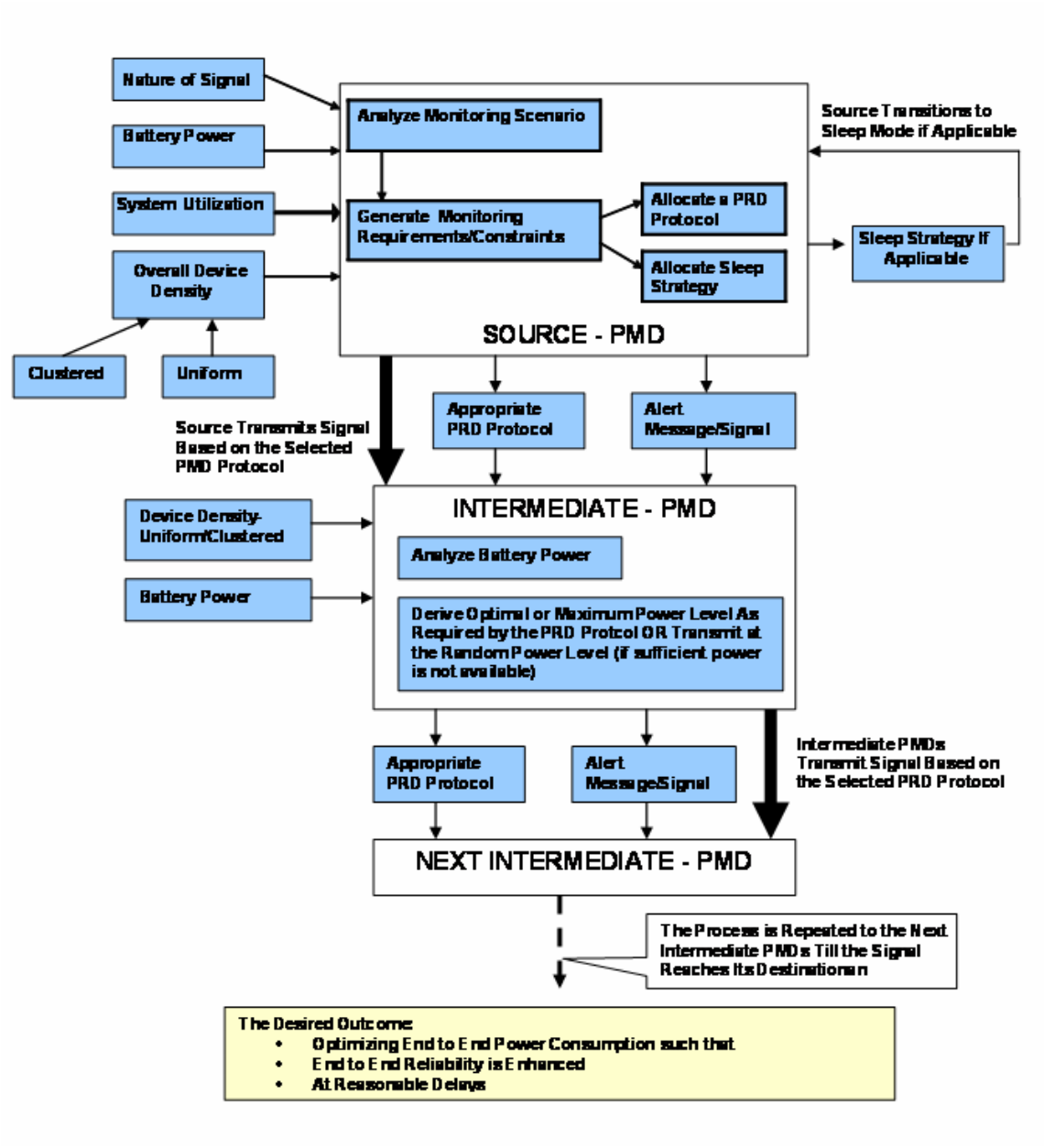


Figure 23: Process Model Underlying the PM-PRD Scheme

CHAPTER 5

RESEARCH METHODOLOGY

The motivation for the current research lies in the lack of comprehensive network support available to most patient monitoring solutions. Sole dependence of most patient monitoring solutions on infrastructure oriented networks which inherently suffer from spotty coverage and unpredictable network support is one of the primary factors negatively affecting the dependability of patient monitoring solutions. The current research explores the potential of utilizing multi-hop MANET to extend the networking support towards comprehensive patient monitoring solutions in areas when the coverage from infrastructure oriented networks is limited or non-existent. There are colossal challenges and promises associated with leveraging multi-hop MANET for patient monitoring.

The current research focuses on efficient utilization of the most critical resource (i.e. battery power of the PMDs) with the goal of enhancing reliability at reasonable delays in end to end signal transmission while considering the constraints/requirements of diverse patient monitoring scenarios. Chapter 4 develops and explains the proposed PM-PRD scheme that analyzes diverse patient monitoring scenarios, assesses the context of a given patient monitoring scenario (in terms of the constraints/requirements), and operationalizes an appropriate power management technique (PRD protocols and/or sleep strategy) in the process of end to end signal transmission. The key performance measures of the effectiveness of the proposed power management techniques and the PM-PRD scheme are: end to end reliability, end to end delays, and end to end power consumption in signal transmission from the source to the destination. The premise underlying end to end signal transmission via the PM-PRD scheme (that operationalizes the PRD protocols and/or sleep

strategy) is associated with maximization of reliability and minimization of power usage at reasonable delays for a given patient monitoring context.

Analytical modeling methodology is utilized in the current research to analytically model and assess the performance of the PRD protocols, sleep strategy, and the PM-PRD scheme in terms of the key performance measures (i.e. end to end power consumption, end to end reliability, and end to end delays in signal transmission). This following sections explain the appropriateness of analytical modeling methodology in the current research, the network model chosen as a case study for conducting performance evaluation, the research model describing the independent/dependent variables, and the detailed steps in performance evaluation.

Appropriateness of Analytical Modeling Methodology

Performance analysis of multi-hop MANET under diverse patient monitoring scenarios can be studied via multiple ways such as a laboratory experiment, field study, or modeling (i.e. analytical and/or simulation). A laboratory experiment to conduct the performance evaluation in the current context would imply assembling the actual physical components that mirror end to end signal transmission under diverse patient monitoring scenarios via a multi-hop MANET, implement the proposed techniques and scheme in a PMD, have a substantial number of patients/users transmit signals, and record the actual impact on the performance measures. However, this approach is not feasible given the constraints of a doctoral dissertation, specifically due to the following reasons: (a) requirements of substantial financial resources to support such a venture which is not typically available to a doctoral

student, (b) implementing and testing the impact of multiple patient monitoring scenarios via actual prototype of a network architecture/a PMD is another challenge that is difficult to meet in the course of a doctoral dissertation due to limited resource/time available in a doctoral dissertation, and (c) having a large number of patients/users actually transmit signals pertaining to health information can pose several privacy and security hazards in an experimental system without fully knowing the outcome.

Alternatively, a field study of an existing environment (such as a hospital or a nursing home) enabling end to end transmission of patient monitoring signals via a multi-hop MANET may be possible. The researcher can carry out interventions needed to create diverse patient monitoring scenarios. Field measurements could be made in the existing environment using real network and users. However, this approach has the following key limitation. Patient monitoring via a multi-hop MANET is a novel, futuristic application that is currently non-existent (to the best of my knowledge). Thus it is not possible to conduct relevant field study and obtain performance measures. Moreover, actual MANETs are not easily available to researchers for the purposed of conducting research. The security and privacy concerns with protected health information make it further difficult to conduct a field study in the context of patient monitoring via a MANET.

Alternatives to creating an actual physical environment (via a laboratory study) or studying an existing multi-hop MANET used for patient monitoring solutions (via a field study) are to model the intended system via analytical or simulation modeling techniques and study the performance of the key measures for diverse scenarios. Both analytical and simulation modeling are well established methodologies for conducting performance evaluation where it is considered infeasible to develop actual prototypes of the system/application to be

evaluated. Simulation modeling involves creating a computer program to represent the network model and affords the ability to manipulate one set of parameters to study its impact on the variables of interest. The key constraint in utilizing simulation modeling technique is associated with creating an intricate computer program, the resource requirements, time restrictions, and the technical limitations of the researcher (with respect to programming) in completing the arduous task of developing pseudo code representing conditions of interest and translating the pseudo code into a computer simulation of a complex application.

Analytical modeling involves utilizing mathematical expressions to represent diverse conditions of interest by making certain assumptions. The researcher develops mathematical expressions between the dependent and the independent variables. By varying the independent variables diverse conditions of interest can be created and the corresponding impact on dependent variables can be measured. While simulation modeling relies on computer programs to produce useful results, analytical modeling relies on computational techniques and analysis. Often analytical modeling is considered more efficient than simulation (Ahluwalia 2006, and Malloy 2003).

Analytical performance measures can be used for computation of performance out of an abstract mathematical model of the real system. In development of analytical expressions, the system behavior is modeled based on mathematical functions. In the current context it allows assessing the effectiveness of the proposed PM-PRD scheme that incorporates the PRD protocols and/or power management techniques. Evaluation in terms of the key performance measures under diverse scenarios in end to end signal transmission (a) *with/without utilizing the PM-PRD scheme* and the allocated power management technique(s), and (b) comparisons of different PRD protocols can also be conducted. Since the basis for analytical performance

evaluation is a mathematical model representing the actual system the modeled system does not need to exist in reality. This affords an efficient method to study futuristic applications and systems.

Given the restrictions and limitations associated with conducting laboratory experiments, field study, and simulation modeling, the performance evaluation of the effectiveness of the proposed PM-PRD scheme and the power management techniques (PRD protocols and sleep strategy) is conducted via analytical modeling methodology. Analytical modeling presents a particularly attractive alternative for investigating the performance of the proposed artifacts in terms of the key performance measures. Analytical modeling is one of the few cost effective and efficient ways of building high-fidelity models of a multi-hop MANET in the context of patient monitoring and to assess performance of the model under investigation. Details of the analytical model, the mathematical expressions defining various conditions via the independent variables, the desired outcome expressed in terms of the dependent variables, the assumptions made, and the corresponding results are detailed in Chapter 6. The following sections describe the network model, the research model, and the plan for conducting performance evaluation via analytical modeling methodology.

NETWORK MODEL

The PM-PRD scheme operationalizing the PRD protocols and/or sleep strategy is applicable to a diverse set of patient monitoring scenarios/requirements and has the potential to sustain: (a) broadcast based routing schemes for both emergency as well as routine transmissions, (b) diverse reliability requirements such as: highest reliability for

emergency transmissions and relatively lower for routine transmissions, (c) diverse monitoring and transmissions such as: alert, continuous, and periodic, (d) diverse location and mobility such as: indoor/outdoor and stationary/mobile patients, (e) scalability requirements – the mobile devices transmitting signal in a multi-hop MANET act as routers thus reducing the load of routing on the base stations when large numbers of messages are being transmitted concurrently, and (f) location management via technologies such as RFID (radio frequency identification) and GPS (Global Positioning System) incorporated in the patient's device.

To limit the complexity of modeling and evaluation the network model utilized as a case study in the current research considers end to end signal transmission solely via a multi-hop MANET. The network environment that supports transmission is 802.11. Figure 24 presents a representation of the network model showing signal transmission from patient X to the healthcare professional Y to occur in absence of network support from an infrastructure oriented network. Hence signal transmission from patient X to the healthcare professional Y takes place via a multi-hop MANET following the path X-A-B-C-D-E-Y.

The network model is based on the illustrative usage scenario (described in chapter 1) of monitoring patients via a multi-hop MANET in a nursing home environment. Although, in reality end to end signal transmissions can potentially take place by a multi-hop MANET in conjunction with an infrastructure oriented networks, however in the context of the current research it is assumed that end to end signal transmission occurs solely via a multi-hop MANET in an environment where network coverage from an infrastructure oriented network is limited or non-existent (see Figure 24).

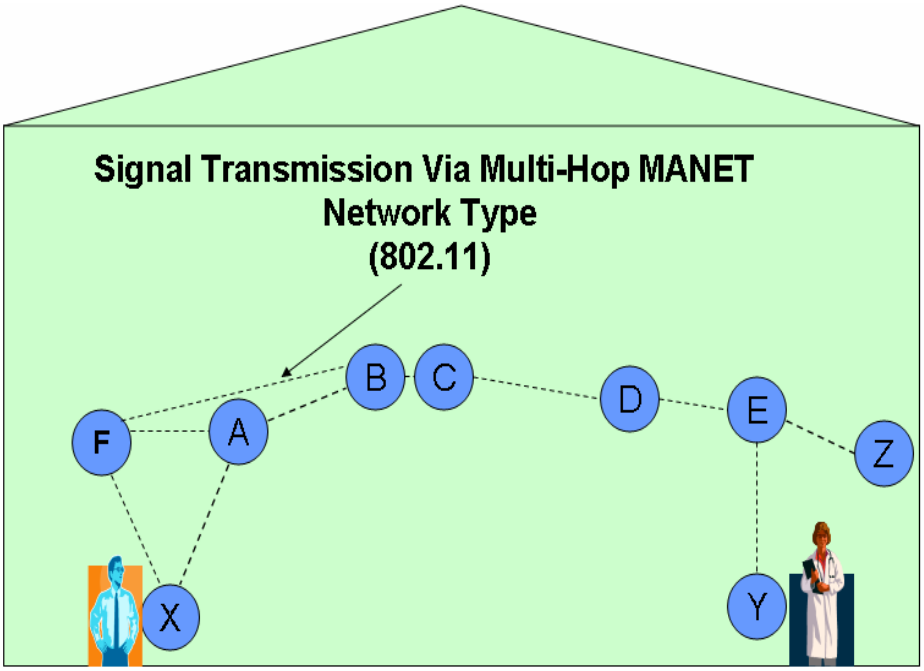


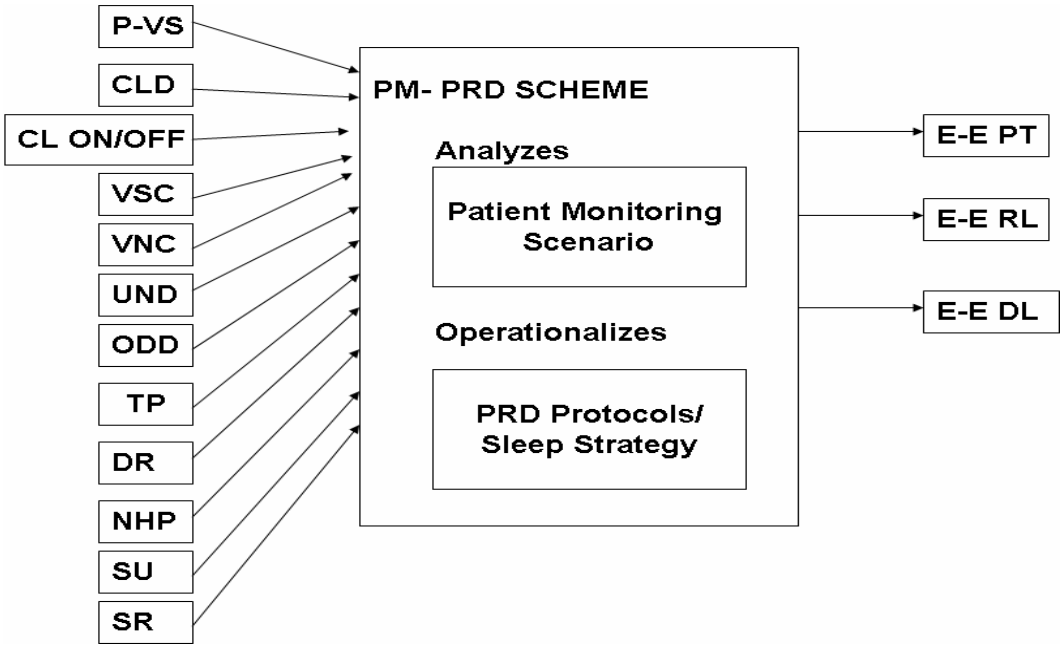
Figure 24: The Network Model – Transmission from X to Y via A-B-C-D-E

To keep the complexity of the model manageable it is assumed that: (a) the PMDs forming the MANET are symmetrical with respect to processing capacity and power, (b) all of the PMDs in a given area of transmission are cooperative routers (i.e. the PMDs within the transmission range are capable of forwarding the signal via the applicable PRD protocol), (c) the PMDs have the resources required to forward the signal at a selected PRD protocol, (d) a given PMD is involved in only one transmission at a given point in time, and (e) signal transmissions are conducted among a given number of patients and a healthcare professional within a pre-specified area (i.e. the nursing home). Moreover, the performance measures are computed for one representative route from the source to the destination involving multiple hops. Performance evaluation of the proposed PRD protocols, sleep strategy, and the PM-PRD scheme is conducted for a wide range of patient monitoring scenarios. Diverse scenarios can

be conducted by varying the independent variables. The details of the research model explicating the key independent and dependent variables is presented in the next section.

RESEARCH MODEL

The research model (see Figure X) including the independent and dependent variables is depicted in Figure 25. The independent and dependent variables are explained in the following sections.



DR = Device Range, NHP = Number of Hops, ODD = Overall Device Density, CLD = Clustered Distribution of Patients, UND = Uniform Distribution of Patients, TP = Power Transmitted by the PMDs at each hop, VSC = Variation in Size of Clusters, VNC = Variation in Number of Clusters, CL ON/OFF = Clusters on/off the route of transmission, P-VS = Patient's Vital Sign (Emergency/Routine), SU = System Utilization, SR = Service Rate of the PMDs involved in End to End Signal Transmission, E-E PT = End to End Power Transmitted, E-E RL = End to End Reliability of Transmission, E-E DL = End to End Delays in Signal Transmission

Figure 25: Research Model

The following tables (i.e. Tables 9, 10, and 11) provide a brief description of the constructs, independent, and dependent variables considered in the current research.

Table 9: Key Constructs in the Current Research

CONSTRUCT	DEFINITION	COMMENT
Source	Patient device initiating signal transmission	The patient device transmits the signal via ad hoc wireless network formed among patient monitoring devices (nodes)
Destination	A Healthcare professional.	The signal is transmitted from source to destination via a pure multi-hop MANET
End to End Signal Transmission	Transmission of signal from the source to destination via a multi-hop MANET	

Table 10: Independent Variables in the Current Research

INDEPENDENT VARIABLE	DEFINITION	COMMENT
Transmitted Power	Power transmitted by each PMD at each hop in the end to end signal transmission	Transmitted power impacts device range at each hop which in turn impacts the number of end to end hops in signal transmission.
Device Range	The range of the transmitting PMD which is dependent on transmitted power at each hop.	Device range defines various possible scenarios pertaining to transmission range of the PMDs forming a MANET for signal transmission
Number of End to End Hops	Total number of hops in end to end signal transmission	Number of end to end hops impacts end to end delays

Uniform Device Distribution	PMDs distributed uniformly in the area of transmission	Impacts overall device density in the transmission area
Clustered Device Distribution	Patient mobility resulting in non-uniform distribution of PMDs in the area of transmission	Impacts overall device density in the transmission area
Variation in Size of Clusters	The clusters vary in size (i.e. the number of PMDs forming the cluster)	Impacts overall device density and the density of the clusters. Overall device density decreases as the size of cluster increases.
Variation in Number of Clusters	The clusters can vary in number (i.e. the number of clusters in the area of transmission)	Impacts overall device density and the density of the clusters. Overall device density decreases as the number of cluster increases.
Clusters On/Off the Route of Transmission	Clusters can be on route and off route of end to end signal transmission	Impacts end to end power transmitted, end to end reliability, and delays
Overall Device Density/ Overall Network Density	The density of PMDs in the area of transmission, some or all of which can route/transmit signal via a multi-hop MANET	Key variable that defines multiple patient monitoring scenarios pertaining to transmission at various device densities
Patient's Vital Sign	Patient's vital sign warranting transmission can be emergency or routine	Variable impacting the constraints with respect to delay tolerance and the choice of PRD protocol for end to end transmission
System Utilization	System utilization defines the transmission load on the system.	Higher the system utilization higher is the end to end delay in signal transmission
Service Rate	Service rate is specific to the PMD and defines the rate at which a signal is processed by a PMD	Higher the service rate lower is the end to end delay in signal transmission

Table 11: The Dependent Variables Considered in the Current Research

DEPENDENT VARIABLE	DEFINITION	COMMENT
End to End Power Transmitted	Total power consumed in end to end signal transmission via a multi-hop MANET	The objective is to optimize/minimize power end to end power usage
End to End Reliability	Reliability in end to end signal transmission expressed in terms of probability of locating cooperative PMDs at each hop in end to end transmission	The objective is to maximize reliability. Reliability always takes high priority in the context of patient monitoring even if it is at the cost of power usage and delays
End to End Delays	Total delays in end to end signal transmission.	The objective is to predict delays in end to end signal transmission via the PRD protocols under diverse patient monitoring scenarios

Objective of Performance Evaluation and the Corresponding Plan

A. Objective of performance evaluation with respect to the PRD protocols:

The PRD protocols seek to utilize variable-rate transmit power by the source and the intermediate routing devices. The desired outcome of utilizing PRD protocols for end to end signal transmission under diverse patient monitoring scenarios are: (a) enhanced reliability, and (b) prediction of power consumption and delays. The anticipated result is maximization of end to end reliability at variable levels of power consumption and delays corresponding to each PRD protocol. Hence the performance evaluation of the PRD protocols is associated with the protocols achieving the anticipated outcome under diverse patient monitoring scenarios.

An overview of the performance evaluation plan with respect to PRD protocols is presented in Table 12. The performance of the key variables (end to end reliability, end to end power, and end to end delays) is measured and recorded under diverse scenarios *with and without utilizing PRD protocols.*

Table 12: Evaluation Plan of the PRD Protocols – Measuring Performance of E-E Reliability, E-E Power Usage, and E-E Delays in Signal Transmission

Variations in Transmitted Power Level With/Without Utilizing PRD Protocols	*Overall Device Density*	
	Uniform Device Distribution	**Clustered Device Distribution**
	No Clusters	**Variation in Size and Variation in Number**
Without Utilizing PRD Protocols - Variations in Fixed-Rate Transmitted Power Resulting in Variations in the Number of End to End Hops.	E-E Power Usage E-E Reliability E-E Delays	E-E Power Usage E-E Reliability E-E Delays
With Utilizing PRD Protocols in End to End Signal Transmission: **RP-RCD, MP-MCD** **MP-OCD, OP-OCD**	E-E Power Usage E-E Reliability E-E Delays	E-E Power Usage E-E Reliability E-E Delays

Performance of key dependent variables in end to end signal transmission without the PRD protocols seeks to validate the relationship of the independent and the dependent variables. Performance of key dependent variables in end to end signal transmission with the PRD protocols seeks to validate that the desired results with respect to reliability, delays, and power usage is achieved. Moreover, the goal of performance evaluation of the PRD protocols

is to validate its utility and discover the best protocol for diverse monitoring scenarios. The performance evaluation does not seek to establish the supremacy of one protocol over another instead it seeks to discover the utility of the protocols under diverse monitoring scenarios. The results are presented in Chapter 6.

B. Objective of performance evaluation with respect to Sleep Strategy:

It is anticipated that sleep strategy reduces overall device density in the area of transmission and can thereby adversely impact end to end reliability, and end to end power consumption. The cost of saving individual device's power is the cost of increased end to end power transmitted in maximizing end to end reliability. Thus the objective of performance evaluation with respect to sleep strategy is limited to exploring and predicting the threshold device density above which sleep strategy can be applicable without adversely impacting end to end reliability and end to end power consumed. The performance of the key metrics with/without utilizing the PRD protocols under diverse scenarios is used to assess the threshold device density.

C. Objective of performance evaluation with respect to PM-PRD Scheme:

The objective of the PM-PRD scheme is to (a) analyze diverse patient monitoring scenarios with respect to the requirements, (b) generate the constraints on end to end reliability and end to end delays, and available power budget, and (c) apply an appropriate PRD protocol and/or sleep strategy that is the best effort to meet the requirements and

constraints of a given patient monitoring scenario. The utility of the PM-PRD scheme is associated with operationalizing the best PRD protocol based on the constraints/requirments of a given patient monitoring scenario. The evaluation of the PM-PRD scheme thus entails discovering the best PRD protocol (in terms of the performance of the PRD protocols with respect to end to end reliability, power usage, and delays) for diverse monitoring scenarios. Consequently, the performance of the PRD protocols for diverse monitoring scenarios in terms of reliability, delays, and power usage in end to end signal transmission is used to assess the utility and accuracy of the PM-PRD scheme in operationalizing the PRD protocols.

CHAPTER 6

ANALYTICAL MODELING

Since implementing the proposed power management techniques and the PM-PRD scheme is not feasible within the scope of the current research (as discussed in detail in Chapter 5) hence analytical modeling methodology is utilized for the purpose of performance evaluation and validation. Analytical modeling offers significantly good accuracy of results and is a well established technique for mathematically modeling various conditions of interest and assessing the performance on the variables of interest. The mathematical model represents relationship between independent and dependent variables. By manipulating the independent variables diverse scenarios of interest can be created and the performance of the dependent variables measured and recorded. Since analytical performance measures are used for computation of performance out of an abstract mathematical model of the real system, the modeled system doesn't need to exist in reality.

Before proceeding to laying out the details of the analytical model, the evaluation plan, and the results, salient assumptions made to keep the complexity of the modeling process manageable are stated below.

- Signal transmission from the source to destination takes place solely via a multi-hop MANET formed among PMDs.
- The PMDs are assumed to be cooperative routers (i.e. the PMDs within the transmission range of a signal are assumed to be willing and capable of transmitting signal further via a MANET till the signal reaches the destination).
- The PMDs are assumed to be symmetrical in processing capacity as well as battery power.

- The network is assumed to be available and have the required bandwidth when signal transmission takes place. Moreover it is assumed that the network doesn't add errors of its own in signal transmission and routing.
- In computing the performance of the key dependent variables one representative route is considered.
- The PMDs are assumed to be involved in one and only one transmission at a given point in time and re-transmissions are not modeled/evaluated.

The list of symbols used in the analytical model and a brief description of each is presented in the Table 13.

Table 13: Parameters and Variables used in the Analytical Model

H_{szij}	Hop size of the transmissions for the i_{th} hop where number of hops = j
D_{un}	Device density considering uniform distribution of devices in the area A
D_{cl}^{k}	Device density considering clustered distribution of devices in the area A, where the number of clusters is denoted by k
D_{cl}	Device density in the cluster
N_{hps}	Number of hops
N_{cl}	Number of clusters
N_{hcl}	Number of hops within a cluster on the route of transmission
N_{dclk1}	Number of devices/users in the cluster k_1
N_{dclk2}	Number of devices/users in the cluster k_2
N_d	Total number of monitoring devices/users in A
P_{ij}	Power transmitted/consumed in the i_{th} hop where number of hops = j.
P_{e2ej}	Total power consumed in the end to end transmission for j number of hops
R_{hij}	Reliability in the i_{th} hop where number of hops = j.

R_{e2ej}	Reliability of end to end transmission for j number of hops
P_{bij}	Probability of locating a device for transmission in the i_{th} hop for j number of hops
P_{be2ej}	Probability of successfully locating devices for complete end to end transmission where number of hops = j
P_{bij}^{CL}	Probability of locating a device for transmission in the i_{th} hop for j number of hops, in the presence of cluster (s)
P_{be2ej}^{CL}	Probability of successfully locating devices for complete end to end transmission where number of hops = j, in the presence of cluster(s)
A	Area of transmission
T_d	Total distance over which transmission of messages takes place in patient monitoring
A_{ij}	Area over which the transmitted message is coherently heard in the i_{th} hop for j number of hops with hop size = H_{szij}
H_{scl}	The hop size within a cluster
P_{hcl}	Power transmitted in each hop within a cluster
P_{bhcl}	Probability of locating a cooperative PMD in each hop within cluster
P_{be2ecl}^{k}	End to End probability of locating a cooperative PMD in each hop within cluster

Parameterization for performance evaluation is based on the following:

- Signal transmission is assumed to take place in a predefined area such as a nursing home. The transmission area is parameterized as a 10 x 10. The end to end transmission distance is 14.14 units.
- The overall device density is varied over a range of 0.5 – 0.05 within the transmission area. For clustered device distribution the overall device density in the area of transmission reduces.
- The number of clusters within the transmission area is assumed to vary. The number of clusters can be parameterized with discrete values = 1, 2.

- The size of clusters within the transmission area is assumed to vary as well. The size of clusters can be parameterized with values = 30% of the PMDs or 40% of PMDs.
- The clusters are assumed to be on/off the route of transmission.
- The number of PMDs in the area of transmission is also assumed to be constant.
- Diverse scenarios involving variations in transmit power are created by varying the device range of all PMDs involved in end to end signal transmission from 1.414 – 7.07 thereby causing the number of end to end hops to vary from 10 to 2 for the given end to end distance.

End to End Reliability of Transmission.

In the current research reliability of end to end transmission is measured in terms of probability of locating a cooperative PMD within the range of a transmitted signal at each consecutive hop in end to end routing of the transmitted message via a multi-hop MANET. The probability of locating a PMD (assuming all PMDs in the area of transmission are cooperative routers) in each hop in end to end signal transmission is a function of (a) the power transmitted at each hop by a PMD and (b) the device density within the range of transmission. Thus the probability of locating a PMD can be expressed as a function:

$$P_{bij} = Function(P_{ij}, DeviceDensity) \quad \textbf{(1)}$$

where P_{bij} = probability of locating a PMD in the ith hop in j number of e-e hops

P_{ij} = Power transmitted in the ith for j number of e-e hops

Device Density = Overall device density in the area of transmission

Transmitted Power

The power transmitted at each hop impacts the corresponding hop size. Power consumed in transmitting a signal over a hop size H_{szij} can be analytically expressed in simple terms as the following:

$$P_{ij} = RP\_\min \times (Const. \times H_{szij}^{\alpha}) \quad \textbf{(2)}$$

where H_{szij} = Hop size in the ith hop for j number of e-e hops

P_{ij} = Power transmitted in the ith for j number of e-e hops

α = propagation constant which theoretically can take value = 2,3,4

Const. = Constant for propagation loss

RP_min = Minimum receiving power required for correct reception at a given level of receiver noise

Since power transmitted by each PMD is assumed to be uniform (i.e. $P_{ij} = P_{ij\pm1}$) in end to end signal transmission hence the corresponding hop size of each PMD is assumed to be uniform as well (i.e. $H_{szij} = H_{szij\pm1}$) for a given route. The number of end to end hops in signal transmission over a given end to end distance (i.e. T_d) can be expressed in terms of the hop size/power transmitted. Number of end to end hops is analytically modeled as:

$$N_{hps} = \frac{T_d}{H_{szij}} \quad \textbf{(3)}$$

where $N_{hps} <= j$

Thus end to end power transmitted for a given N_{hps} over a given T_d is expressed as:

$$P_{e2ej} = \sum_{N_{hps}=1}^{N_{hps}=j} P_{ij} = \sum_{N_{hps}=1}^{N_{hps}=j} (RP\_\min \times (Const. \times H_{szij}^{\alpha})) \quad \textbf{(4)}$$

where P_{e2ej} = End to End Power transmitted

and $N_{hps} = j$

The range of the monitoring device transmitting the signal, is considered to be the circular area with radius equal to the H_{szij}, across which the message can be coherently received by the intermediary monitoring device(s). The intermediate PMDs transmit the signal further till it reaches the destination. Analytical expression of the device range is:

$$A_{ij} = \pi \times H_{szij}^{2} \quad \textbf{(5)}$$

where A_{ij} = area/device range in the ith hop for j number of e-e hops

Hop Size for the ith hop can be expressed as:

$$H_{szij}^{2} = \left[\left(\frac{P_{ij}}{RP\_\min \times Const.} \right)^{1/\alpha} \right]^{2} \quad \textbf{(6)}$$

Thus device range can be expressed as:

$$A_{ij} = \pi \times H_{szij}^2 = \pi \times \left[\left(\frac{P_{ij}}{RP\_\min \times Const.} \right)^{1/\alpha} \right]^2 \quad \textbf{(7)}$$

Overall Device Density: Considering Uniform Device Distribution

Overall device density in the area of transmission is a key determinant of probability of locating cooperative PMDs in end to end signal transmission. Overall device density depends on the device distribution. In this section the analytical expression of overall device density is derived considering uniform device distribution in the area of transmission, A uniform device density is expressed as:

$$D_{un} = \frac{N_d}{A} \quad \textbf{(8)}$$

where $N_d =$ total number of PMDs in the area of transmission

Reliability of transmission for Uniform Device Distribution

Reliability of transmission at each hop expressed in terms of probability of transmission at each hop considering uniform device distribution is analytically expressed as follows:

$$P_{bij} = A_{ij} \times D_{un} = \left[\pi \times \left(\left[\left(\frac{P_{ij}}{RP\_\min \times Const.} \right)^{1/\alpha} \right]^2 \right) \right] \times \left[\frac{N_d}{A} \right] \quad \textbf{(9)}$$

The end to end reliability of signal transmission measured in terms of end to end probability of locating a PMD in each consecutive hop in end to end signal transmission is a direct function of P_{bij} in each successive hop. In the case of uniform device density and constant hop size, $P_{bij} = P_{bij\pm1} \quad \exists 1 \le i \le j$ and N_{hps} = j. Hence the probability of locating PMDs in each consecutive hop in transmitting the signal from the source to the destination via a multi-hop ad hoc network where can be approximated as:

$$P_{be\,2\,ej} = \prod_{N_{hps}=1}^{N_{hps}=j} P_{bij} = \prod_{N_{hps}=1}^{N_{hps}=j} \left[\left\{ \pi \times H_{szij}^{2} \right\} \times \left\{ \frac{N_d}{A} \right\} \right] \qquad \textbf{(10)}$$

P_{be2ej} can be further expressed in terms of the transmitted power as following:

$$P_{be\,2\,ej} = \prod_{N_{hps}=1}^{N_{hps}=j} \left[\left\{ \pi \times \left(\left[\left(\frac{P_{ij}}{RP\_\min \times Const.} \right)^{1/\alpha} \right]^2 \right) \right\} \times \left\{ \frac{N_d}{A} \right\} \right] \qquad \textbf{(11)}$$

Performance of end to end reliability measured in terms of end to end probability under diverse scenarios is assessed by varying (a) the transmitted power by each PMD in end to end signal transmission and (b) the overall device density. Variation in transmitted power is manifested in terms of variations in the number of end to end hops expressed as:

$N_{hps} <= j$ where **2 <= j <= 10** in end to end signal transmission.

$$N_{hps} = \frac{T_d}{H_{szij}}$$ where **1 <= i <= j.**

Hop size expressed in terms of transmitted power utilizing equation 6 is:

$$H_{szij} = \left[\left(\frac{P_{ij}}{RP\_\min \times Const.} \right)^{1/\alpha} \right] \quad \textbf{(12)}$$

Thus N_{hps} can be further expressed in terms of transmitted power as:

$$N_{hps} = \frac{T_d}{\left[\left(\frac{P_{ij}}{RP\_\min \times Const.} \right)^{1/\alpha} \right]} \quad \textbf{(13)}$$

where N_{hps} varies from 2 to 10.

Diverse scenarios with respect to overall device density in the area of transmission are expressed in terms of variation in device density over a range as expressed as the following:

$$0.05 <= D_{un} <= 0.5 \quad \textbf{(14)}$$

The probability of end to end transmission depends on the probability of finding a co-operative device for routing the transmitted signal. The probability of locating a node for transmission in the i_{th} hop considering the number of hops to be = j, is a function of device density and the power emitted in the i_{th} hop. Power emitted by the routing device in the i_{th}

hop is a function of hop size for the i_{th} hop considering j number of hops. Probability of successful end to end transmission is directly related to the device density for a given level of transmitted power by the PMDs in end to end signal transmission. As the density of monitoring devices increases so does the probability of locating a node for transmission for the given level of transmitted power. A decrease in emitted power decreases hop size and can negatively impact the probability of locating cooperative PMDs for further transmission especially in the instances involving low device density.

Modeling Clustering and the Corresponding Impact on End to End Reliability

Mobility of patients within a given area could lead to non-uniform distribution such as clustering thus negatively impacting the overall device density in the area of transmission. Since probability of locating a device for end to end transmission has a positive relationship with overall device density in the area of transmission, consequently clustering has an adverse impact on probability of successful transmission which measures reliability. The impact of clustering on overall device density is modeled by varying the size and the number of clusters. The clusters are also modeled as being on and off the route of transmission. The analytical model and the underlying assumptions with respect to modeling the impact of clusters on overall device density which determines reliability are as follows:

- The clusters are circular with:

$$radius = \frac{H_{szij}}{2} \quad \textbf{(14)}$$

$$area = \pi \times \left(\frac{H_{szij}}{2} \right)^2 \quad \textbf{(15)}$$

- Device density in a cluster D_{clk} is given by:

$$\frac{NumberofDevicesInCluster}{ClusterArea} \quad \textbf{(16)}$$

- The number of clusters, N_{cl} is either 1 or 2. Thus $N_{cl} = 1$ OR $N_{cl} = 2$
- The variations in cluster sizes are: 30% or 40% of N_d
- The variations in number of clusters are: **(A)** 1 cluster with either 30% or 40% of N_d and **(B)** 2 clusters each with 30% of N_d or 40% of N_d. Each of the two variations of clusters is also modeled as being on and off the route of transmission. The results show the impact of the variations with respect to cluster on reliability and device density.

A. Modeling Variations in Size and Number of Clusters

Let L = the number of devices forming a cluster. The rest of the modeling for cluster based transmission assumes that L takes on one of the four values given by the following equations:

(I) For $N_{cl} = 1$, if N_{dcl}^{k1} is the number of devices in a cluster where k1 stands for $N_{cl} = 1$ then:

$$L = \begin{cases} N_{dcl}^{k1} = 0.3 \times N_d \\ \quad OR \\ N_{dcl}^{k1} = 0.4 \times N_d \end{cases} \quad \textbf{(17)}$$

(II) For $N_{cl} = 2$, if N_{dcl}^{k2} is the number of devices in a cluster where k2 stands for $N_{cl} = 2$ then modeling the value of **L** where the 2 clusters have 30% of N_d or 40% of N_d each is as follows:

$$L = \begin{cases} N_{dcl1}^{k2} = N_{dcl2}^{k2} = 0.3 \times N_d \\ \quad OR \\ N_{dcl1}^{k2} = N_{dcl2}^{k2} = 0.4 \times N_d \end{cases} \quad \textbf{(18)}$$

Therefore device density in the clusters is given by the following equation, considering L is the number of devices forming a cluster.

$$D_{clk} = \frac{L}{\pi \times \left(\frac{H_{szij}}{2} \right)^2} \quad \textbf{(19)}$$

If there is a cluster present in the route of transmission, then the transmission within the cluster takes place via smaller hops. The number of hops within the cluster N_{hcl} is impacted by the number of devices forming the cluster. So theoretically the route within the cluster can take the smallest possible hop size and go through multiple smaller hops. However, the problem with that is a longer route with considerable delays. Hence the current

research puts a ceiling on N_{hcl} irrespective of the number of devices forming the cluster in order to complete the transmission within a reasonable time, which is a critical requirement of patient monitoring. Therefore $1 <= N_{hcl} <= 4$. The value of N_{hcl} is derived by the minimum value of the number of devices in the cluster or 4:

$$N_{hcl} = Minimum\,(L, 4) \quad \textbf{(20)}$$

The hop size within a cluster, H_{scl}, is considered to be the uniform for each hop irrespective of N_{hcl}. It follows that the value of H_{scl} is given by:

$$H_{scl} = \frac{H_{szij}}{N_{hcl}} \quad \textbf{(21)}$$

Consequently the power transmitted for each hop (h) in a cluster is also uniform and is expressed as follows:

$$P_{hcl} = RP\_\min \times (Const. \times H_{scl}^{\alpha}) \quad \textbf{(22)}$$

End to End power transmitted in the cluster is expressed as:

$$P_{e2ecl} = \sum_{1}^{N_{hcl}} RP\_\min \times (Const. \times H_{scl}^{\alpha}) \quad \textbf{(23)}$$

The probability of locating a device in each successive hop, h, within the cluster is:

$$P_{bhcl} = R_{hcl} \times D_{clk} \quad \textbf{(24)}$$

$$P_{bcl} = \left(\pi \times H_{scl}^{2}\right) \times \left(\frac{L}{\pi \times \left(\frac{H_{szij}}{2} \right)^{2}} \right) \quad \textbf{(25)}$$

End to end probability of successful transmission within the cluster where $N_{cl} = 1$ or $N_{cl} = 2$ is given by

$$P_{be\ 2\ ecl} = \prod_{1}^{N_{hcl}} P_{bcl} \quad \textbf{(26)}$$

The impact on overall device density in the area of transmission due to the presence of clusters is modeled as follows:

$$D_{cl} = \frac{N_d + N_{cl} - (L \times N_{cl})}{A} \quad \textbf{(27)}$$

Hence, the presence of cluster(s) results in a decrease in overall device density in the area of transmission. The effective decrease in the number of uniformly distributed devices due to clustering is compensated to some extent by the number of clusters formed since each cluster acts as one big node in the otherwise uniformly distributed nodes.

The probability of locating a device for transmission in the i^{th} hop for j number of hops, in the presence of cluster (s) is approximated as:

$$P_{bij}^{CL} = \pi \times H_{szij}^{\ 2} \times D_{cl} \quad \textbf{(28)}$$

Thus the probability of locating devices for successful end to end transmission considering j number of hops, and N_{cl} = k where *cluster(s) in the route of transmission* is given by:

$$P_{be\,2\,ej}^{CL} = \prod_{i=1}^{j-k} P_{bij}^{CL} \times \prod_{k=1}^{k} P_{be\,2\,ecl}^{\ k} \quad \textbf{(29)}$$

It follows that probability of locating devices for successful end to end transmission considering j number of hops, and N_{cl} = k where *cluster(s) are not in the route of transmission* is given by:

$$P_{be\,2\,ej}^{CL} = \prod_{i=1}^{j} P_{bij}^{CL} \quad \textbf{(30)}$$

The probability of transmission in the presence of clusters is relatively lower than the probability of transmission in the absence of clusters. The reason is associated with the decrease in overall density in the area of transmission. The worst case scenario involves clusters not in the route of transmission. The probability of successful end to end transmission is the lowest in this case since the overall user density is lowered and the transmissions cannot leverage the clustered devices for further routing.

Modeling (PRD) Power-Reliability-Delay Protocols

The performance of the protocols is measured in terms of end to end reliability, end to end delays, and end to end power consumption by utilizing the protocols in signal transmission from the source to the destination. For modeling the PRD protocols it is assumed that all transmissions take place according to the allocated protocol. RP-RCD and MP-MCD are anticipated to be not impacted by variability in overall device density in the area of transmission. Hence the performance of end to end power transmitted as well as end to end delays in RP-RCD and MP-MCD is anticipated to stay constant over variable range of overall device density in the area of transmission. On the other hand since MP-OCD and OP-OCD are impacted by the overall device density in the area of transmission hence the performance of end to end power transmitted as well as end to end delays in MP-OCD and OP-OCD is anticipated to vary with the variations in overall device density in the area of transmission.

Random Power from the Patient and Cooperative Routing Devices (RP-RCD)

Power levels from the patient and intermediate devices are generated randomly for transmitting the signal to the healthcare provider via multiple hops. For RP-RCD, the patient and the cooperative routing devices generate a random number between 0 and 3. Each number corresponds to a specific power level among the four power levels (Min, Med, High, and Max). For modeling RP-RCD each of the four power levels correspond to a specific hop size from the following set (1.414, 2.828, 4.242, and 7.07). The nodes transmit at random power levels till the signal reaches a healthcare provider or comes within the range of an infrastructure based network. Since P_t is random in each hop, it is difficult to predict P_t in the successive hops. Consequently the total power transmitted in end to end transmission varies and so does reliability and delays. RP-RCD is considered the worst case scenario. The

processing involved in RP-RCD is limited to generating a random number and selecting a transmit power level for each hop in end to end transmission.

A number 0 → Min → Hop Size = 1.414 → $P_t = RP\_\min \times (Const. \times 1.414^{\alpha})$ **(31)**

A number 0 → Min → Hop Size = 2.828 → $P_t = RP\_\min \times (Const. \times 2.828^{\alpha})$ **(32)**

A number 0 → Min → Hop Size = 4.242 → $P_t = RP\_\min \times (Const. \times 4.242^{\alpha})$ **(33)**

A number 0 → Min → Hop Size = 7.070 → $P_t = RP\_\min \times (Const. \times 7.070^{\alpha})$ **(34)**

Maximum Power from the Patient and Cooperative Routing Devices (MP-MCD)

MP-MCD is modeled on the assumption that the messages are always transmitted at a predetermined maximum level. Since the PMDs are assumed to be symmetrical hence the maximum power level is uniform across all devices. For MP-MCD power transmitted by all PMDs is maximum such that the hop size in each hop = 7.070. The corresponding power transmitted at each hop in end to end signal transmission is expressed as:

$$P_t = RP\_\min \times (Const. \times 7.070^{\alpha}) \quad \textbf{(35)}$$

Optimal Power from the Patient and Cooperative Routing Devices (OP-OCD)

If P_t is the power transmitted and P_n is the minimum power required to reach the nearest node with 100% reliability then optimal power level for transmission is expressed as the state where:

$$\lambda = P_t - P_n \qquad \ni \lambda \to 0 \quad \textbf{(36)}$$

The value of optimal power level is a function of device density in the area of transmission. The value of optimal power levels at various levels of device density and power transmitted is iteratively derived by considering the minimum hop size corresponding to minimum number of hops where the probability of successful end to end transmission is 100%. For instance: if the device density is 0.5, then the maximum number of hops or minimum hop size at which end to end probability of transmission is 100% is 10 hops corresponding to a hop size = 1.414. Thus for OP-OCD when overall device density = 0.5, the power transmitted at each hop corresponds to $P_t = RP\_\min\times(Const.\times 1.414^{\alpha})$, it follows that $\lambda \to 0$.

Maximum from the Patient and Optimal from the Cooperative Routing Devices (MP-OCD)

The patient's device transmits at the maximum power level such that the hop size = 7.070. The remaining distance is covered by the intermediate routing devices at the optimal power level based on the device density in the area of transmission as calculated for OP-OCD.

Modeling End to End Delays

End to End delay is calculated using M/M/1 queue. Assuming symmetry in the service rate of the PMDs, the service rate (**μ**) of the PMDs is 100 packets per second (i.e. a PMD takes 0.01 second to process a packet). System utilization (**r**) is varied over 0 to 0.9.

Arrival rate of packets (**λ**) is calculated by the following expression:

$$r = \frac{\lambda}{\mu} \qquad \textbf{(37)}$$

Queue length is expressed as:

$$Q = \left(\frac{r \times 2}{1 - r} \right) \quad \textbf{(38)}$$

Waiting time is expressed as:

$$T_q = \left(\frac{r/\mu}{1 - r} \right) \quad \textbf{(39)}$$

Service time is expressed as:

$$T_s = \frac{1}{\mu} \quad \textbf{(40)}$$

Total time in each hop (i.e. ith hop in j number of hops) is expressed as:

$$T_i = T_q + T_s = \left[\left(\frac{r/\mu}{1 - r} \right) + \left(\frac{1}{\mu} \right) \right] \quad \textbf{(41)}$$

End to End Delay is then expressed as:

$$D_{e2e}^{j} = \sum_{N_{hps}}^{N_{hps} = j} \frac{1/\mu}{1 - r} \quad \textbf{(42)}$$

Performance of End to End Delay is assessed for varying hops at varying levels of system utilization.

Plan for Performance Evaluation

Table 14 outlines the plan for performance evaluation and the corresponding results that are presented in the following section. The structure of the plan is based on the Table 12 from Chapter 5.

Table 14: Structure of Performance Evaluation

<table>
<tr><td rowspan="3">Variations in Transmitted Power Level With/Without Utilizing PRD Protocols</td><td colspan="3">Overall Device Density Varied Under Uniform/Clustered Device Distribution Scenarios</td></tr>
<tr><td>Uniform Device Distribution</td><td colspan="2">Clustered Device Distribution</td></tr>
<tr><td>C=0</td><td>C=1, Size = 30%, 40%</td><td>C=2, Size = 30%, 40%</td></tr>
<tr><td>Without Utilizing PRD Protocols –
Variations in Transmitted Power Manifested in terms of Variations in N_{hps}.
$N_{hps}=10$, $N_{hps}=9$
$N_{hps}=8$, $N_{hps}=7$
$N_{hps}=6$, $N_{hps}=5$</td><td>E-E Reliability</td><td>E-E Reliability</td><td>E-E Reliability</td></tr>
<tr><td colspan="3">E-E Power Usage, E-E Delays

E-E Power Usage and E-E Delays in the case of transmissions without the PRD protocols are a function of hop size and number of end to end hops and not a function of device density in the area of transmission. (Please see equations 4, and 42)Hence the performance of E-E Power Usage and E-E Delays are anticipated to be the same across varying levels of overall device density.</td></tr>
<tr><td>With Utilizing PRD Protocols in End to End Signal Transmission:
RP-RCD
MP-MCD
MP-OCD
OP-OCD</td><td>E-E Power Usage
E-E Reliability
E-E Delays</td><td>E-E Power Usage
E-E Reliability
E-E Delays</td><td>E-E Power Usage
E-E Reliability
E-E Delays</td></tr>
</table>

PERFORMANCE OF E-E RELIABILITY, E-E POWER USAGE, AND E-E DELAYS

The analytical model is utilized for the evaluation of reliability metrics, delays, and power management protocols under varying conditions. The objective is to optimize limited resources with respect to battery power and enhance reliability at reasonable delays. The results show that it is possible to achieve 100% reliability in end to end signal transmission while optimizing power usage and predicting delays by operationalizing the proposed PRD protocols via the PM-PRD scheme. The results that were found significant for the current study are presented and discussed.

The performance of the reliability metric (i.e. probability of successful end to end transmission), end to end power consumed, and end to end delays is evaluated by varying conditions pertaining to (1) device density (allocated between 0.05 – 0.5 units), (2) uniform distribution (N_{cl} = 0) versus clustered distribution of devices (i.e. N_{cl} = 1 or 2), (3) number and size of cluster(s) (i.e. N_{dcl}^{k1} = 30% of N_d or 40% of N_d OR N_{dcl}^{k2} = 30% of N_d or 40% of N_d), and (4) clusters being on/off the route of transmission. The value of the power transmitted constants (i.e. $RP\_\min\times Const.$) is parameterized as = 1, and the value of α =2. The variation in power transmitted is manifested in terms of varying the number of end to end hops, such that 2<= N_{hps} <=10 over the given end to end distance T_d .

The results of performance evaluation and the corresponding discussions are presented in the next section for various scenarios.

RESULTS OF PERFORMANCE EVALUATION WITHOUT UTILIZING PRD PROTOCOLS

This section presents results corresponding to the performance of end to end power usage, delays, and reliability without using the PRD protocols in end to end signal transmission. The results are consistent with prior discussions (in Chapter 3 and 4) and validate that (a) end to end power usage, delays, and reliability are significantly impacted by the independent variables considered in devising various monitoring scenarios and (b) end to end reliability is not always maximized in diverse scenarios manifested by variations in number of end to end hops (i.e. power transmitted by the PMDs) and overall device density.

Case1: Varying E-E Hops and Overall Device Density for Uniform Device Distribution (C=0)

This section presents the impact of varying (a) transmitted power in end to end signal transmission (manifested in terms of variations in end to end hops), and (b)varying overall device density in the area of transmission considering the case of uniform device distribution (i.e. the instance in which there are no clusters, C=0). The results conclusively validate the inverse relationship of power conservation with reliability and end to end delays. As the number of end to end hops increase (due to decreased power transmitted at each hop and a corresponding decrease in the hop size) the end to end power consumed decreases. However the cost of power conservation is the corresponding increase in end to end delays (over varying levels of system utilization) and decrease in end to end reliability at low levels of device density in the area of transmission.

Figure 26 shows that end to end power consumed increases exponentially with a decrease in the number of end to end hops. The result validates that multi-hop transmission optimizes battery power. The reduction in power usage can potentially be by a factor of $N_{hps}^{\alpha-1}$ by transmitting signals over a distance of T_d via N_{hps} instead of transmitting via a single hop. The increase in end to end power consumed is non-linear. In the current case the increase in end to end power transmitted is less significant till the number of end to end hops = 5. For all other transmissions where number of end to end hops is less than 5 the end to end power transmitted take an exponential shape.

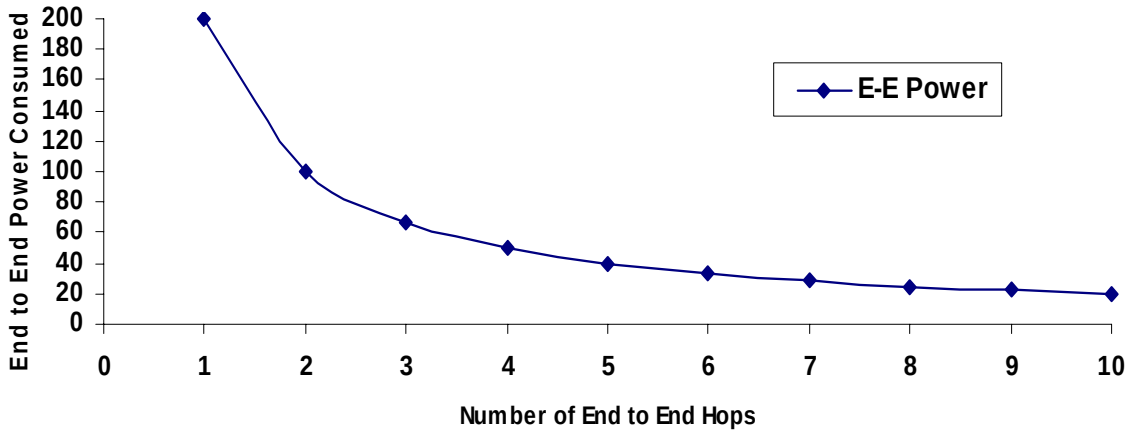


Figure 26: E-E Power Usage as a Function of Variation in E-E Hops

Figure 27 shows that performance of end to end reliability increases non-linearly as the number of end to end hops decreases for a given level of overall device density and end to end distance(i.e. as the power transmitted in end to end signal transmission increases). Moreover, the result shows that cases of low overall device density requires high power utilization corresponding to a decrease in the number of end to end hops in order to maximize

end to end reliability in signal transmission. As the device density increases so does the reliability of end to end transmission for varying levels of end to end hops. Notwithstanding is the fact that the threshold device density (in this case) at/above which end to end reliability of transmission is maximized at 100% for varying levels of end to end hops (i.e. end to end power transmitted) is = 0.2. Thus sleep strategy can be applied when overall device density > 0.2 in the area of transmission. Applying sleep strategy below the threshold device density will lead to decrease in end to end reliability for a given level of end to end hops. Thus maximizing end to end reliability (100%) at decreased device density will lead to increased utilization of battery power. In the current case, all transmissions with number of end to end hops <=5 the end to end reliability is maximized at 100% over the entire range of device density due to increase in transmitted power at each hop which compensates for reduced device density. Thus minimal power consumption at low levels of overall device density (i.e. ODD <= 0.2) such that end to end reliability is 100% corresponds to signal transmissions at the power level at which number of end to end hops = 5 for the given T_d .

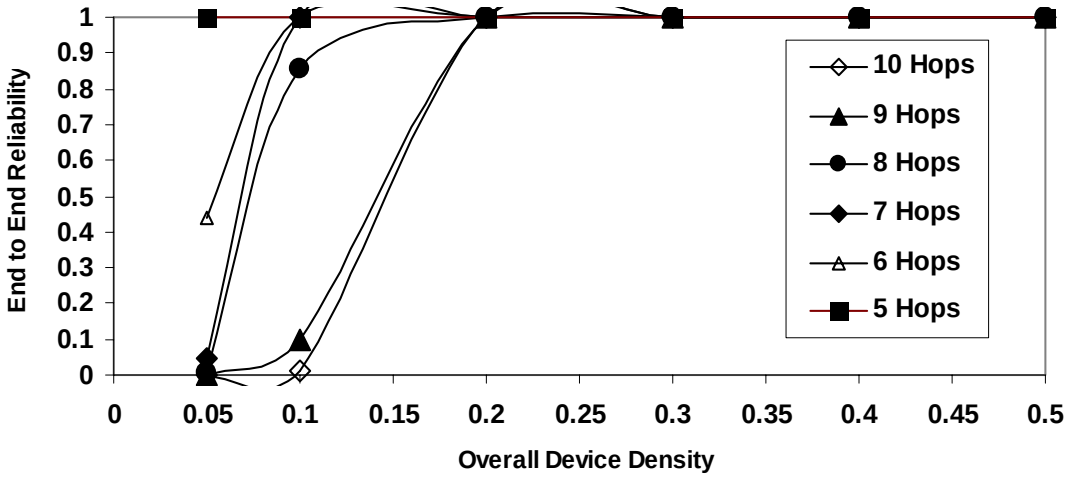


Figure 27: E-E Reliability as a Function of Variation in Device Density and E-E Hops

Figure 28 shows that end to end delays increases significantly as the number of end to end hops increases for varying levels of system utilization. The end to end delays shows a low gradient in increase when the system utilization is less than 50% (approximately) beyond which end to end delay increase exponentially. Thus at low levels of system utilization power conservation can be maximized by transmitting power at the lowest level (i.e. increasing number of end to end hops) such that end to end reliability is not adversely impacted. At high levels of system utilization, reduction in end to end delays can lead to potentially higher power usage. The results also substantiate the inverse relationship of end to end delays with end to end power usage. For instance the end to end power usage is minimum at 10 hops whereas the end to end delays are maximum for 10 hops at varying levels of system utilization.

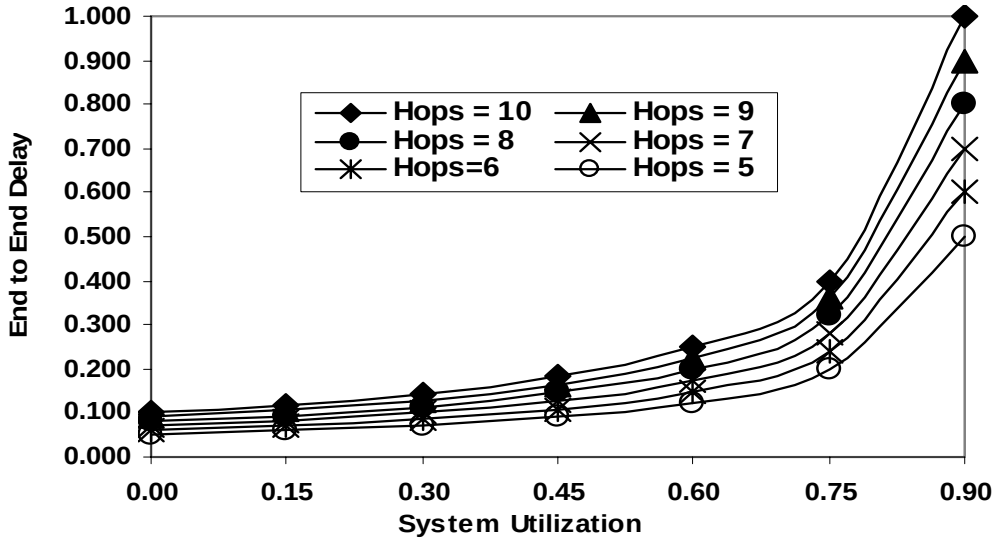


Figure 28: E-E Delays as a Function of Variation in System Utilization and E-E Hops

Case2: Varying E-E Hops and Overall Device Density for Clustered Device Distribution

This section presents the impact of varying (a) transmitted power in end to end signal transmission (manifested in terms of variations in end to end hops), and (b)varying overall device density in the area of transmission considering the case of clustered device distribution (i.e. the instance in which there are clusters in the area of transmission). Variations in overall device density are associated with scenarios pertaining to patient mobility in the area of transmission resulting in clustered device distribution. Since end to end power usage and end to end delays are not functions of variations in overall device density (see equations 4, 42) hence only the performance analysis of end to end reliability is presented. Results and corresponding performance analysis pertaining to variations in number of end to end hops and variations in size of clusters, number of clusters, and clusters being on/off the route of transmission, are explicated in the following sections. The results (see Figures, 29, 30, 31, 32) are consistent with prior discussion of the impact of clustered distribution on overall device density and end to end reliability in the area of transmission (Chapter 3). The results further confirm that end to end reliability is not always maximized in diverse monitoring scenarios associated with variations in overall device density and transmitted power.

(A) Cluster = 1, Size = 30% and 40% of PMDs in Transmission Area, Clusters On and Off the Route of End to End Transmission

This section presents results corresponding to the performance of end to end reliability in the presence of 1 cluster, on/off the route of transmission consisting of 30%/40% of PMDs in the area of transmission. As a result effectively 70%/60% of the total PMDs is distributed

uniformly in the area of transmission. Consequently, in the presence of clusters the overall device density in the area of transmission decreases. For a given number of PMDs in the area of transmission, the range of D_{cl} in the presence of 1 cluster with 30% of N_d decreases to 0.04 - 0.36 and the range of D_{cl} in the presence of 1 cluster with 40% of N_d decreases to 0.04 - 0.31 whereas the corresponding range of device density is 0.05 - 0.5 in case of uniform device distribution for a fixed number of PMDs. The decrease in D_{cl} reduces the reliability of end to end transmission over the entire range of variations in N_{hps}. For instance the overall device density of 0.2 (for C=0) corresponds to 0.15/0.13 (for C=1 at 30%/40% of PMDs) and the associated end to end reliability for 10 hops is 100% (for C=0), 58% (for C=1 at 30% of PMDs), and 16% (for C=1 at 40% of PMDs). Thus the results validate that the performance of end to end reliability decreases further as the size of cluster increases. The end to end reliability when the size of cluster = 40% of PMDs is lower than the end to end reliability when the size of cluster = 30% of PMDs for variations in N_{hps}. Additionally, the results show that the decrease in end to end reliability for variations in N_{hps} is slightly more pronounced when the clusters are off the route of end to end transmission (see Figure 30 and Figure 32 depicting results for cluster off the route of transmission for different sizes). The results also show that end to end reliability decreases for higher values of N_{hps} especially in instances of low overall device density. Notwithstanding is the observation that in case of 1 cluster varying in size and the cluster being on/off the route of transmission, the minimal N_{hps} at which end to end reliability is maximized at 100% still corresponds to 5 hops for a given T_d. Moreover, it can be approximated that sleep strategy in case of 1 clusters can only be applied for relatively higher levels of overall device density. The threshold device density at which sleep strategy can be applied in case of 1 clusters consisting of 30% of PMD is equal to 0.22 which corresponds to

0.3 in case of uniform device density (i.e. a uniform device density of 0.3 shrinks to 0.22 in case of clustered device density) (see Figures 29, 30). In case of 1 clusters consisting of 40% of PMDs the threshold device density at which sleep strategy can be applied without adversely impacting end to end reliability and end to end power used is 0.19 that corresponds to 0.3 in case of uniform device density (i.e. a uniform device density of 0.3 shrinks to 0.19 in case of clustered device density) (see Figures 31, 32).

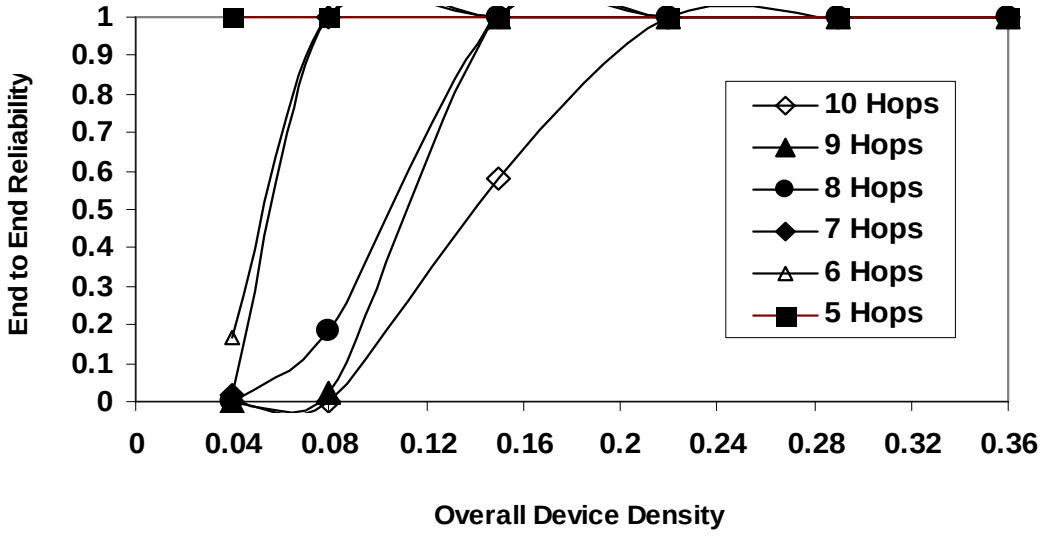


Figure 29: E-E Reliability as a Function of Variation in Device Density and E-E Hops In the Presence of C=1, 30% of PMDs, Cluster on Route of Transmission

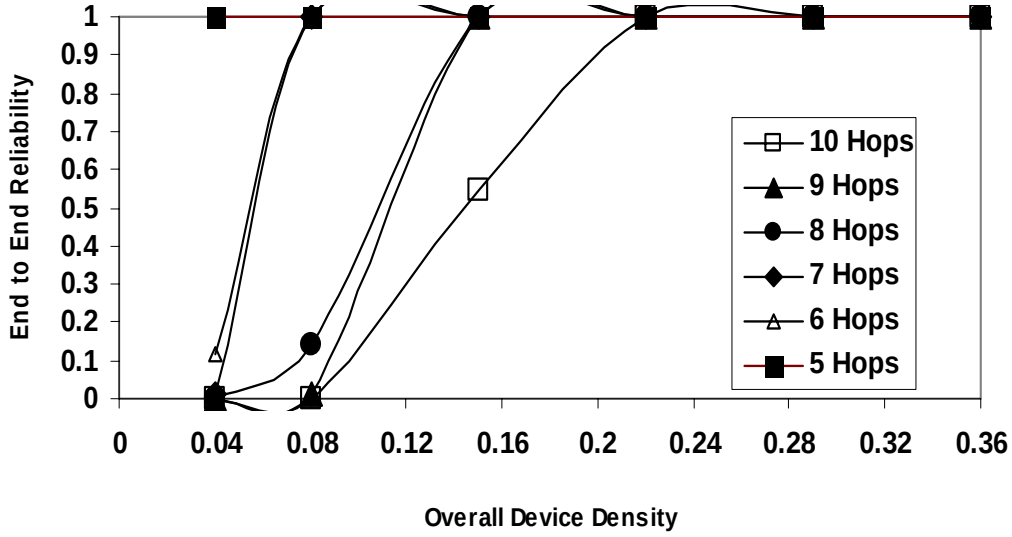


Figure 30: E-E Reliability as a Function of Variation in Device Density and E-E Hops In the Presence of Cluster = 1, Size = 30% of PMDs, Cluster Off Route of Transmission

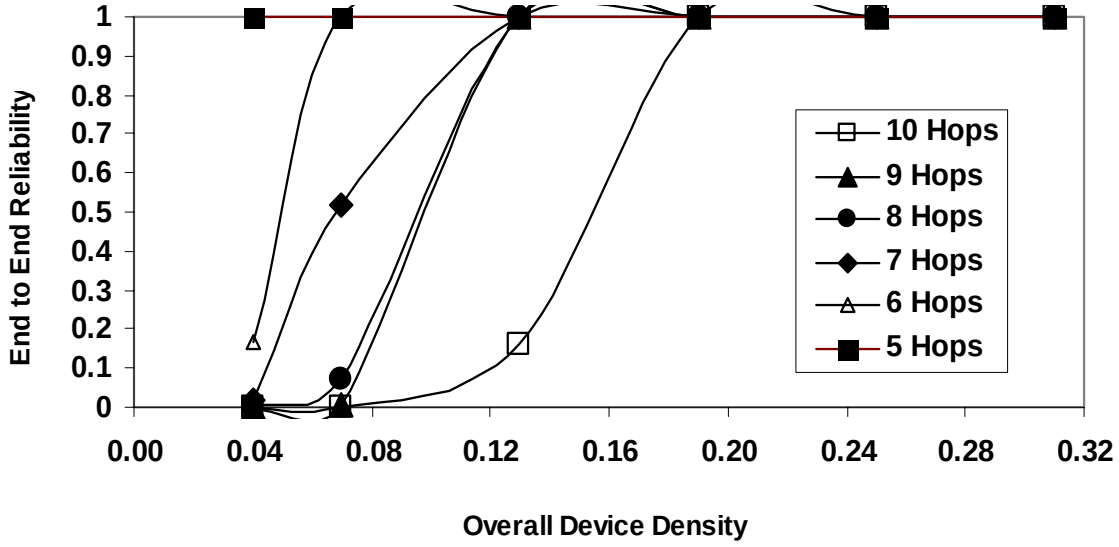


Figure 31: E-E Reliability as a Function of Variation in Device Density and E-E Hops In the Presence of Cluster = 1, Size = 40% of PMDs, Cluster On Route of Transmission

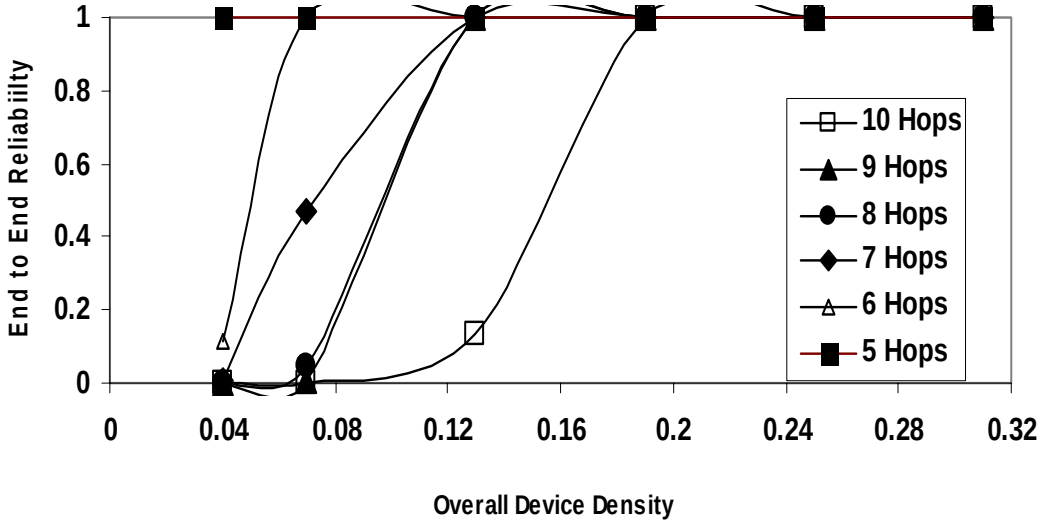


Figure 32: E-E Reliability as a Function of Variation in Device Density and E-E Hops In the Presence of Cluster = 1, Size = 40% of PMDs, Cluster Off Route of Transmission

(B) Clusters = 2, Size = 30% and 40% of PMDs in Transmission Area, Clusters On and Off the Route of End to End Transmission

This section presents results corresponding to the performance of end to end reliability in the presence of 2 cluster, on/off the route of transmission, each consisting of 30%/40% of PMDs in the area of transmission. As a result effectively 40%/20% of the total PMDs in the area of transmission is distributed uniformly in the area of transmission. Consequently, in the presence of 2 clusters the overall device density in the area of transmission decreases significantly. For a given number of PMDs in the area of transmission, the range of D_{cl} in the presence of 2 cluster with 30% of N_d decreases to 0.03 - 0.22 and the range of D_{cl} in the presence of 1 cluster with 40% of N_d decreases to 0.03 - 0.12 whereas the range of device

density is 0.05 - 0.5 in case of uniform device distribution. The decrease in D_{cl} reduces the reliability of end to end transmission over the entire range of variations in N_{hps}. Moreover, the results validate that the performance of end to end reliability decreases non-linearly as the number of cluster increases. The end to end reliability when the number of cluster = 2 with 30%/40% of PMDs is significantly lower than the end to end reliability when the number of cluster = 1 with 30%/40% of PMDs over the entire range of variations in N_{hps}. Additionally, the results show that the decrease in end to end reliability for variations in N_{hps} is slightly more pronounced when the clusters are off the route of end to end transmission (see Figure 34 and Figure 36 depicting results for cluster off the route of transmission for variations in sizes). One critical observation is that in end to end transmissions involving two clusters of varying sizes and clusters being on/off the route of transmission the minimal N_{hps} at which end to end reliability is maximized for variable levels of overall device density = 4 whereas the corresponding minimal $N_{hps} = 5$ for cluster = 1 or 0. Consequently, much higher end to end power transmitted is required to maximize reliability at 100% for variable levels of overall device density in the case of 2 clusters (see Figures 33,34,35,36). Additionally it is to be noted that for 2 clusters when the size of clusters is increased to 40% of PMDs then for $N_{hps} = 10$ and 9, the end to end reliability never reaches 100%. The reason for that is the disproportionate reduction in overall device density in the area of transmission due to the formation of clusters. Moreover, it can be approximated that applicability of sleep strategy in case of 2 clusters is risky and can only be applied for very high levels of overall device density. The threshold device density at which sleep strategy can be applied in case of 2 clusters consisting of 30% of PMD is equal to 0.18 which corresponds to 0.4 in case of uniform device density (i.e. a uniform device density of 0.4 shrinks to 0.18 in case of clustered device

density) (see Figures 33, 34). In case of 2 clusters consisting of 40% of PMDs there is no threshold device density at which sleep strategy can be applied without adversely impacting end to end reliability since there is no single value of overall device density at which end to end reliability is maximized at 100% across the entire range of end to end hops (see Figure 35, 36).

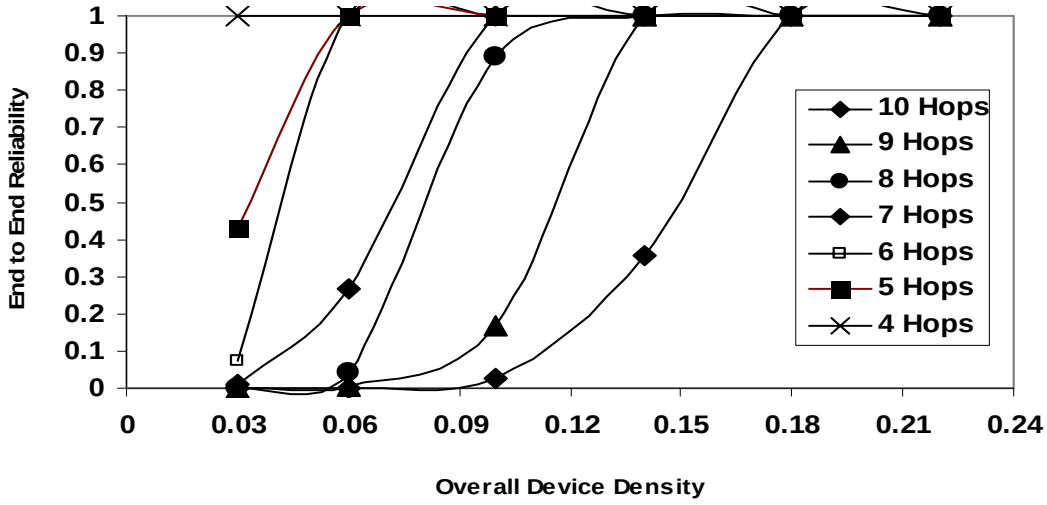


Figure 33: E-E Reliability as a Function of Variation in Device Density and E-E Hops In the Presence of Cluster = 2, Size = 30% of PMDs, Cluster On Route of Transmission

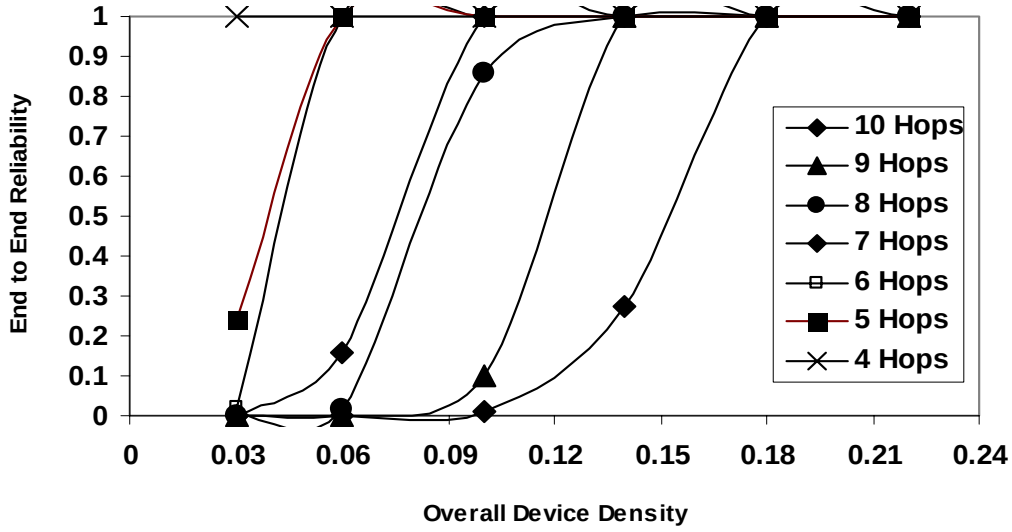


Figure 34: E-E Reliability as a Function of Variation in Device Density and E-E Hops In the Presence of Cluster = 2, Size = 30% of PMDs, Cluster Off Route of Transmission

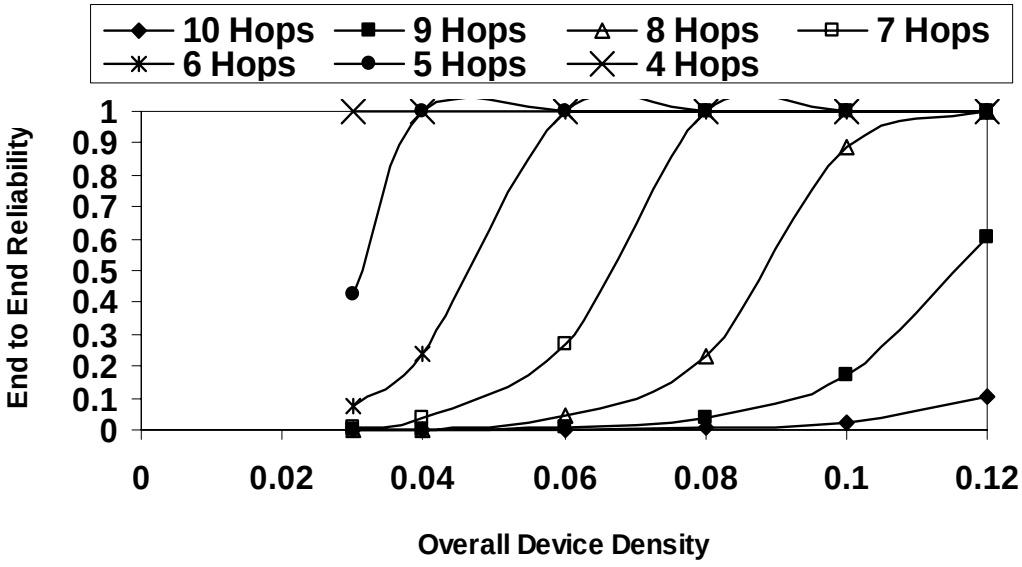


Figure 35: E-E Reliability as a Function of Variation in Device Density and E-E Hops In the Presence of Cluster = 2, Size = 40% of PMDs, Cluster On Route of Transmission

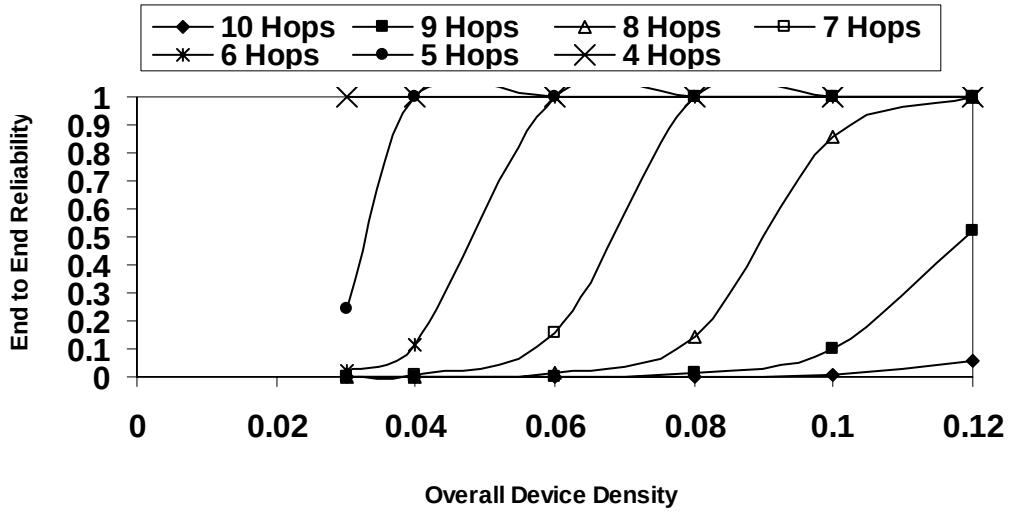


Figure 36: E-E Reliability as a Function of Variation in Device Density and E-E Hops In the Presence of Cluster = 2, Size = 40% of PMDs, Cluster Off Route of Transmission

(C) Comparative Performance Evaluation of End to End Reliability for Varying End to End Hops and Clusters Varying in Number, Size, On/Off the Route of Transmission

This section presents comparative performance analysis of end to end reliability for 10 hops and 8 hops as a function of variations in size, number, and presence of clusters on/off the route of transmission (see Figure 37, 38). The results in both the figures consistently validate that uniform device distribution (denoted by C=0) is the best case scenario for the performance of end to end reliability and as the number/size of cluster increases corresponding performance of end to end reliability decreases. The performance of end to end reliability for clusters being on/off the route of transmission in 10 hops as well as 8 hops doesn't show very significant differences. The small difference in performance can be attributed to transmissions taking advantage of in-cluster routing. For 10 hops, the case of 2

clusters with 40% of PMDs in each shows that the performance of end to end reliability never gets to 100% (even for very high levels of overall device density) whereas in contrast the performance of end to end reliability for 10 hops in uniform distribution reaches 100% reliability at device density = 0.2. For 8 hops the performance of end to end reliability shows improvement compared to 10 hops such that for the case of 2 clusters with 40% of PMDs in each the end to end reliability reaches 100% for very high levels of overall device density. The comparative performance evaluation of end to end reliability of transmission in the presence of varying sizes and number of clusters for 10 and 8 hops respectively validate that $R_{e2e10} > R_{e2e10}^{1c30\%s} > R_{e2e10}^{1c40\%s} > R_{e2e10}^{2c30\%s} > R_{e2e10}^{2c40\%s}$.

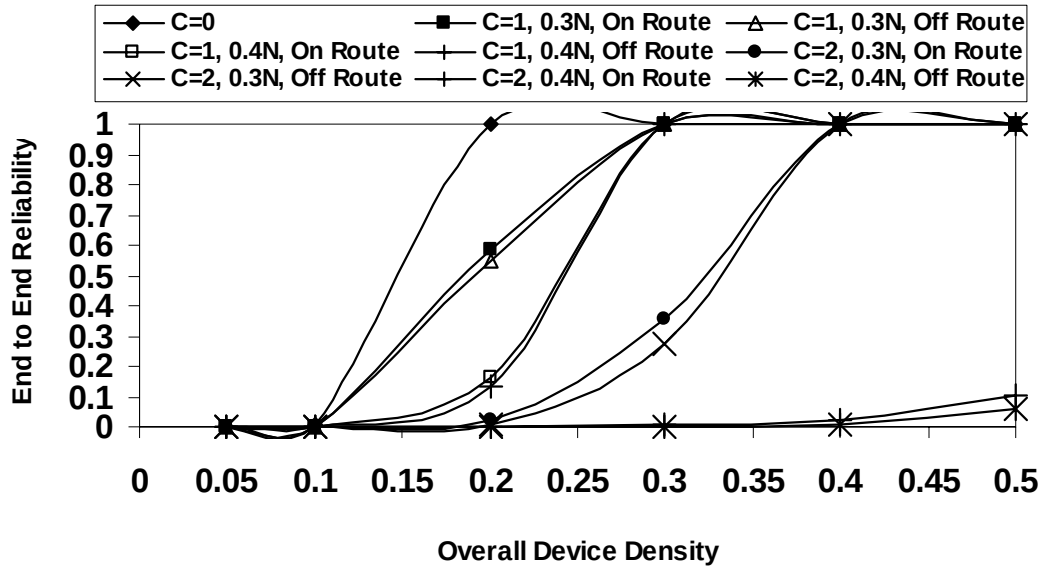


Figure 37: E-E Reliability for 10 E-E Hops and Variable Overall Device Density Due to Variations in Cluster Size, Number, and Clusters On/Off Route

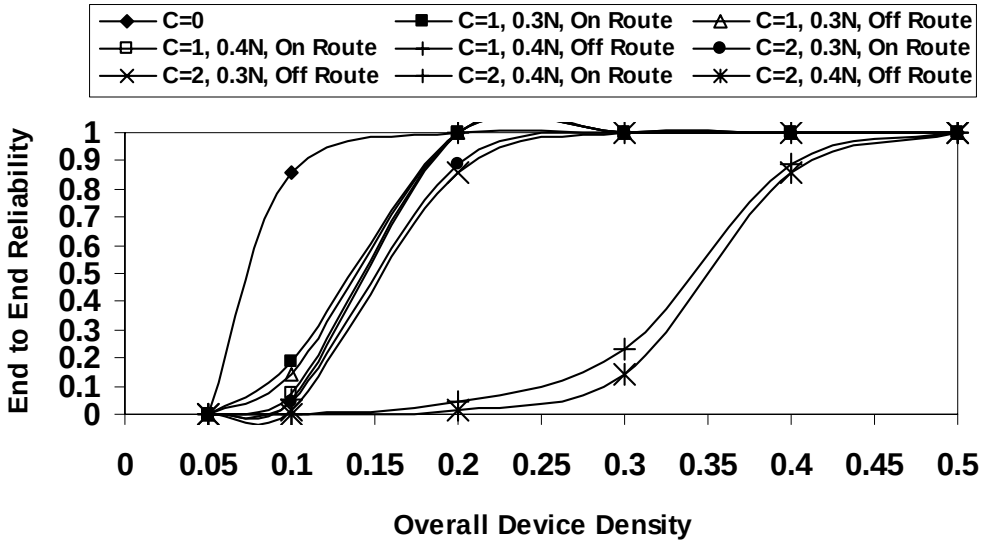


Figure 38: E-E Reliability for 8 E-E Hops and Variable Overall Device Density Due to Variations in Cluster Size, Number, and Clusters On/Off Route

RESULTS OF PERFORMANCE EVALUATION WITH UTILIZING PRD PROTOCOLS

This section presents results corresponding to the performance of end to end power usage, delays, and reliability with using the PRD protocols in end to end signal transmission. The results are consistent with prior discussions (chapter 4) and validate that the PRD protocols maximize end to end reliability for diverse monitoring scenarios manifested by variations in overall device density. The analysis of end to end power consumed and end to end delays in signal transmission further validate the accuracy of the PM-PRD scheme in allocating an appropriate PRD protocol that reflects the best effort in meeting the requirements/constraints of diverse monitoring scenarios. The results show that the relative performances of end to end power consumption and delays remain constant as a function of the PRD protocols for diverse scenarios (pertaining to variations in overall device density)

although the absolute values change (i.e. OP-OCD is most power efficient protocol and the least delay efficient protocol under variable scenarios pertaining to overall device density and system utilization). Moreover, the results show that the performance of end to end delays has a positive relationship with overall device density for varying levels of system utilization. Another critical observation is that whereas transmission due to clustering typically has an adverse impact on end to end power consumption it has a favorable impact on end to end delays for variable levels of system utilization (see Figure X, X,X – E-E Delays in the presence/absence of clusters). The reason is associated with increased transmitted power in order to maximize end to end reliability at low levels of overall device density thereby leading to reduction in number of end to end hops and a corresponding reduction in end to end delays. A closer assessment of the performance as explained in the following sections corroborates the effectiveness of the PM-PRD scheme in protocol allocation for end to end signal transmission.

Performance of PRD Protocols for Uniform Device Distribution

This section presents results with respect to the PRD protocols. The results validate that the utilizing PRD protocols in signal transmission maximizes end to end reliability of transmission (at 100%) associated with OP-OCD, MP-OCD, and MP-MCD (see Figure 40). In contrast signal transmissions without the PRD protocols failed to maximize end to end reliability under similar conditions. The variations in these protocols is specifically related to end to end power consumption which leads to variations in end to end hops and corresponding end to end delays. RP-RCD is the worst case scenario where end to end power transmitted, end to end reliability, and end to end delays in transmission is unpredictable and difficult to gauge since it performs randomly at each hop. The result in Figure 39 shows the impact of

the protocols on end to end power consumption at varying levels of overall device density. As expected, OP-OCD offers the highest level of efficiency in power consumption while maintaining 100% reliability of end to end transmission, followed by MP-OCD. At lower levels of device density the transmitted power is higher in order to maintain high levels of reliability and then levels off as the density of monitoring devices increases to 0.2 units. The power consumed by the protocols RP-RCD and MP-MCD in end to end signal transmission is independent of the device density in the area of transmission due to the protocols' behavior of transmitting at a random level of power and a maximum level of power, respectively (see Figure 39). Moreover, end to end power transmitted for protocols OP-OCD and MP-OCD has an inverse relationship with overall device density due to higher level of power transmitted to maximize reliability at lower levels of device density in the area of transmission see Figure 39). The performance of end to end delays with respect to the PRD protocols at varying levels of system utilization is presented in Figures 42, 43, 44. MP-MCD as expected affords the lowest delays (due to minimum number of end to end hops) for varying levels of system utilization while OP-OCD has the highest delays in end to end signal transmission (due to longer route involving more hops than other protocols). The performance of RP-RCD varies as expected. The end to end delays increases non-linearly as the system utilization increases. For OP-OCD the performance of end to end delays at 15% of system utilization reaches a maximum value of 0.12, the corresponding value at 45% of system utilization reaches a maximum value of 0.18, whereas the value at 90% system utilization reaches a maximum value of 1.00. Thus system utilization plays a significant role in the performance of end to end delays. End to end delays has a positive relationship with overall device density for variable levels of system utilization (see Figures 41, 42, 43, 44). While MP-MCD is the least power efficient protocol it is the best protocol with respect to the performance of end to end delays. On the other hand while OP-OCD is affords the best efficiency in power consumption it

has the worst performance with respect to end to end delays for varying levels of system utilization. Hence MP-MCD is potentially the best suited for emergency transmission with high delay constraints while OP-OCD is best suited for routine transmissions with lower delay constraints. These assessments and allocations are consistent with the PM-PRD scheme.

Case 1: Results for Cluster = 0

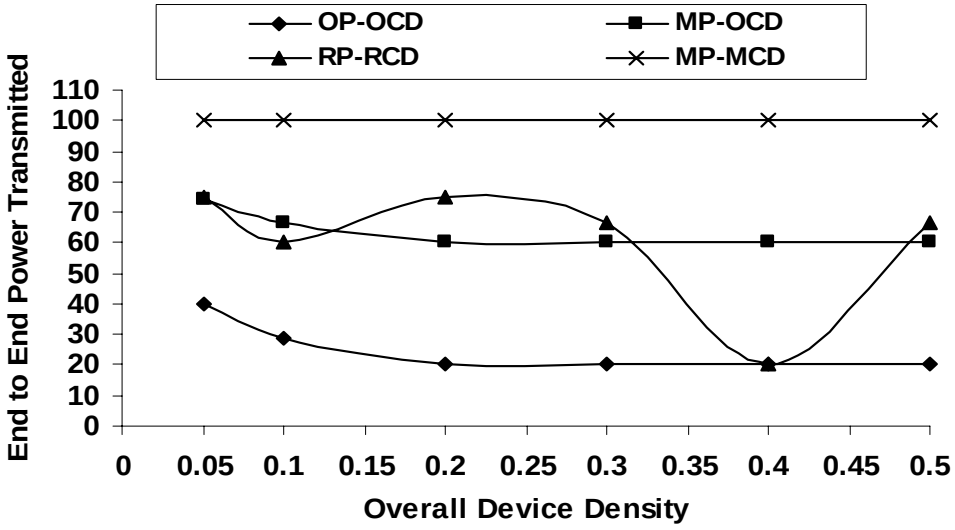


Figure 39: End-End Power Transmitted for Uniform Device Distribution, C=0

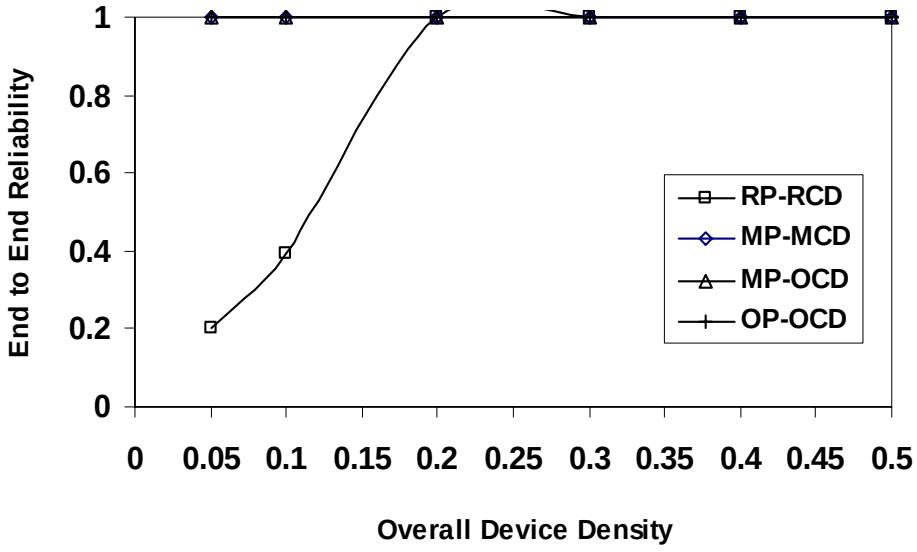


Figure 40: End-End Reliability of Transmission for Uniform Device Distribution (C=0)

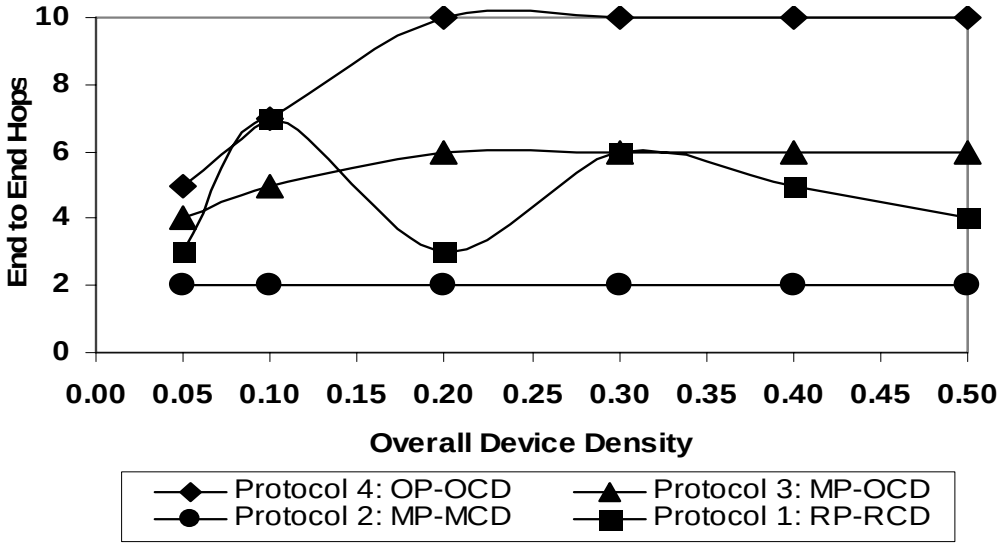


Figure 41: End to End Hops for Uniform Device Distribution, C=0

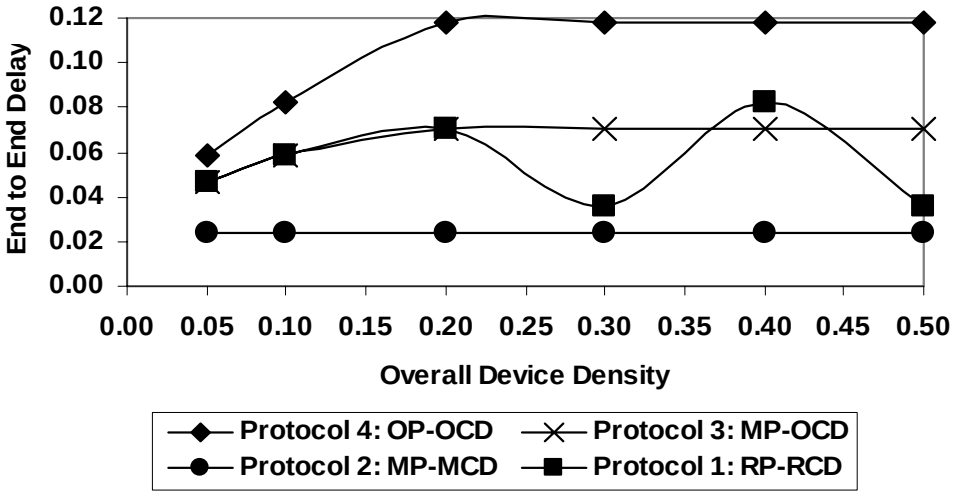


Figure 42: End-End Delays in Transmission for Uniform Device Distribution (C=0) at System Utilization = 15%

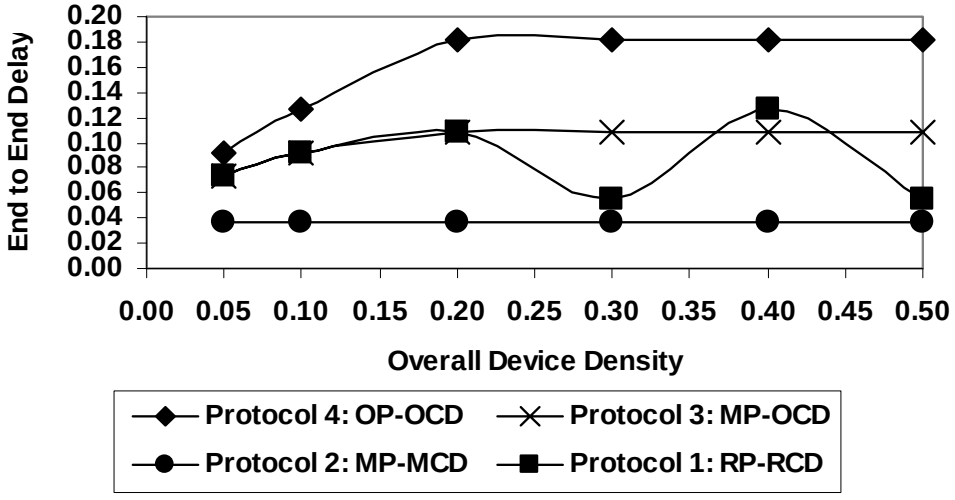


Figure 43: End-End Delays in Transmission for Uniform Device Distribution (C=0) at System Utilization = 45%

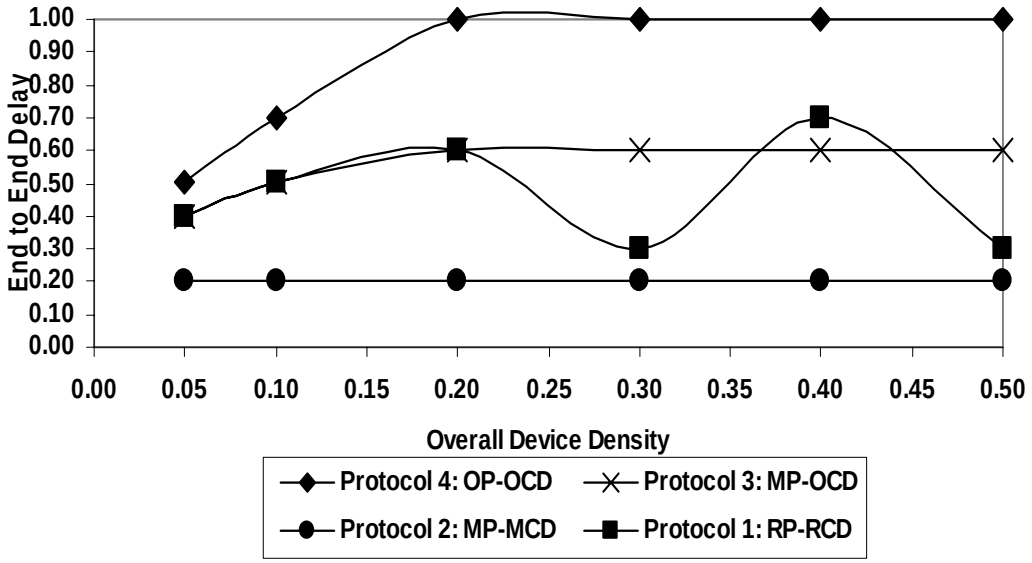


Figure 44: End-End Delays in Transmission for Uniform Device Distribution (C=0) at System Utilization = 90%

Performance of PRD Protocols for Clustered Device Distribution

This section presents results with respect to the PRD protocols in the presence of clusters (Clusters = 1 and 2) consisting of 30% of the PMDs in the area of transmission. The results validate that the utilizing PRD protocols in signal transmission maximizes end to end reliability of transmission (at 100%) associated with OP-OCD, MP-OCD, and MP-MCD (see Figure 46, 52). In contrast signal transmissions without the PRD protocols failed to maximize end to end reliability under similar conditions. The PRD protocols successfully maximize end to end reliability (at 100%) for various scenarios pertaining to overall device density even in the case of clustering. The variations in these protocols is specifically related to end to end power

consumption which leads to variations in end to end hops and corresponding end to end delays. RP-RCD is the worst case scenario where end to end power transmitted, end to end reliability, and end to end delays in transmission is unpredictable and difficult to gauge since it performs randomly at each hop.

The result in Figures 45 and 51 shows the impact of the protocols on end to end power consumption at varying levels of overall device density. As expected, OP-OCD offers the highest level of efficiency in power consumption while maintaining 100% reliability of end to end transmission, followed by MP-OCD. At lower levels of device density the transmitted power is higher in order to maintain high levels of reliability and then levels off as the density of monitoring devices increases to 0.15 (for C=1) and 0.10 (for C=2). The power consumed by the protocols RP-RCD and MP-MCD in end to end signal transmission is independent of the device density in the area of transmission due to the protocols' behavior of transmitting at a random level of power and a maximum level of power, respectively (see Figure 45). Moreover, end to end power transmitted for protocols OP-OCD and MP-OCD has an inverse relationship with overall device density due to higher level of power transmitted to maximize reliability at lower levels of device density in the area of transmission.

The performance of end to end delays with respect to the PRD protocols at varying levels of system utilization is presented in Figures 47, 48, 49, 50, 53, 54, 55, and 56. MP-MCD as expected affords the lowest delays (due to minimum number of end to end hops) for varying levels of system utilization while OP-OCD has the highest delays in end to end signal transmission (due to longer route involving more hops than other protocols). The performance of RP-RCD varies as expected. The end to end delays increases non-linearly as the system utilization increases. For OP-OCD the performance of end to end delays at 15% of system

utilization reaches a maximum value of 0.12, the corresponding value at 45% of system utilization reaches a maximum value of 0.18, whereas the value at 90% system utilization reaches a maximum value of 1.00. Thus system utilization plays a significant role in the performance of end to end delays. Additionally, the results point to a critical observation pertaining to the performance of the PRD protocols with respect to the relationship of end to end delays with reduction in overall device density caused due to clustering. The results point out that end to end delays has a positive relationship with clustering and reduction in overall device density in the case of transmissions via the PRD protocols. As the number/size of clusters increases the overall device density in the area of transmission decreases thereby leading to increased end to end power transmitted in order to maximize end to end reliability (assuming that the devices have sufficient battery power to compensate for decrease in overall device density. As a result there is a decrease in end to end hops and a parallel decrease in end to end delays. While MP-MCD is the least power efficient protocol it is the best protocol with respect to the performance of end to end delays. On the other hand while OP-OCD affords the best efficiency in power consumption it has the worst performance with respect to end to end delays for varying levels of system utilization. Hence MP-MCD is potentially the best suited for emergency transmission with high delay constraints while OP-OCD is best suited for routine transmissions with lower delay constraints. These assessments and allocations are consistent with the PM-PRD scheme.

Case2: Results for Cluster=1, Size = 30% of PMDs, Cluster on Route of Transmission

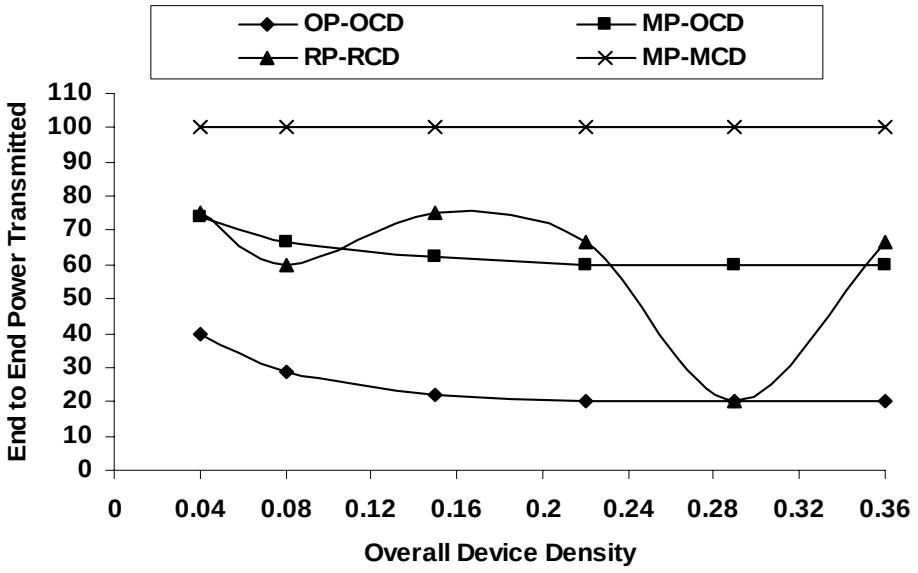


Figure 45: End-End Power Transmitted in Clustered Device Distribution, C=1, 30% of PMD

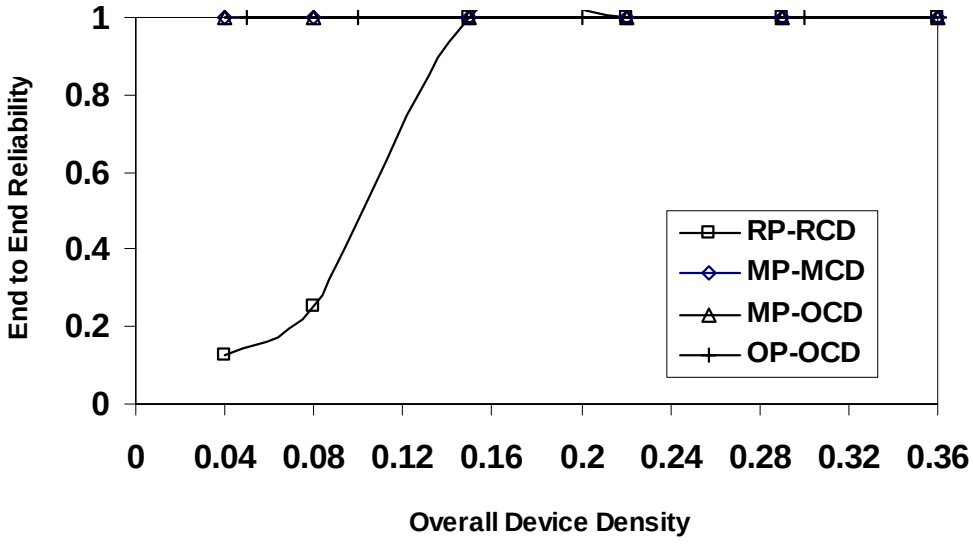


Figure 46: End-End Reliability in Clustered Device Distribution C=1, 30% of PMD

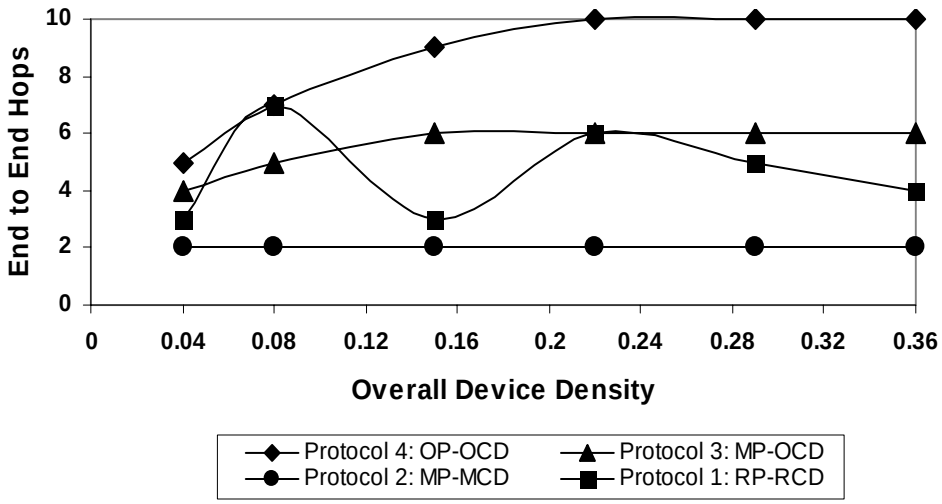


Figure 47: End to End Hops for Uniform Device Distribution, C=1, 30% of PMDs

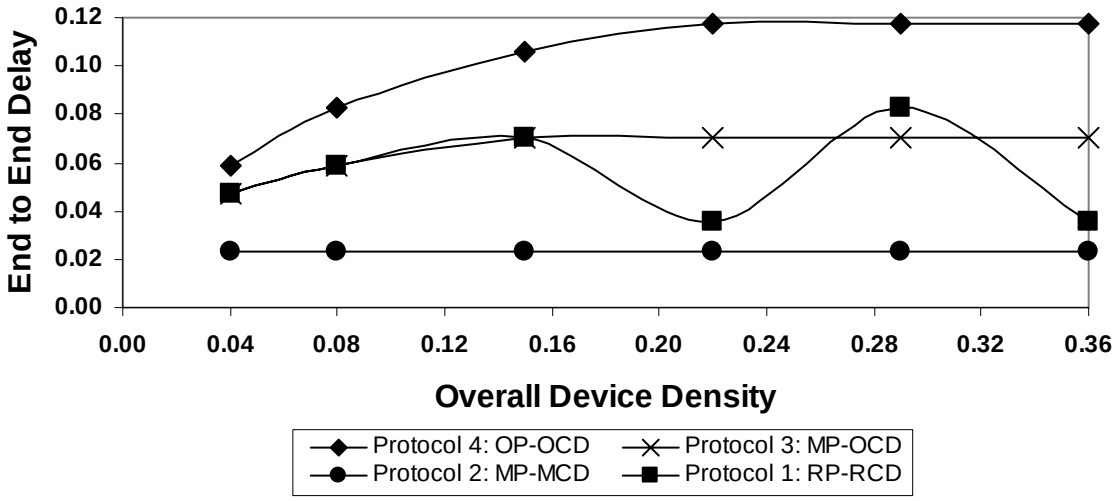


Figure 48: End-End Delays in Clustered Device Distribution (C=1, 30% of PMDs) at System Utilization = 15%

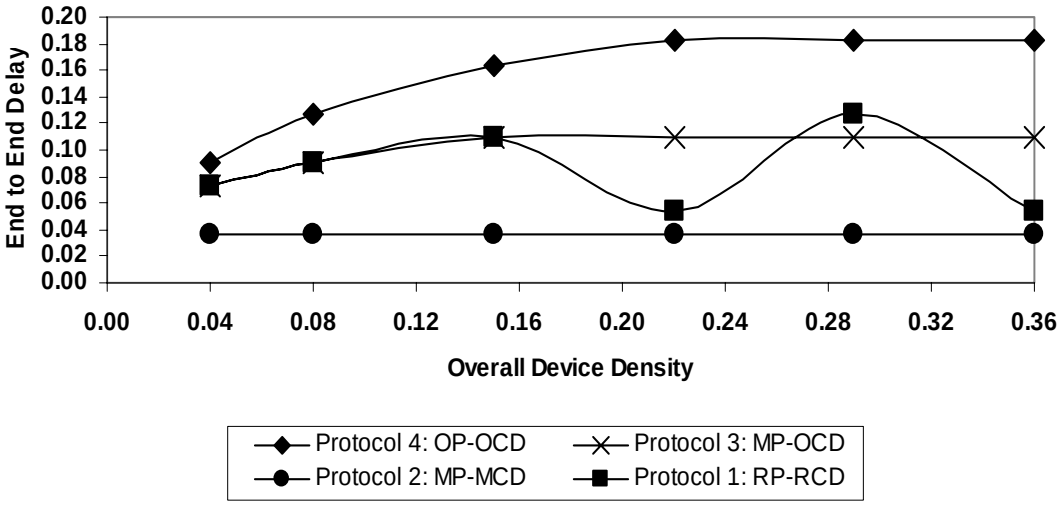


Figure 49: End-End Delays in Clustered Device Distribution (C=1, 30% of PMDs) at System Utilization = 45%

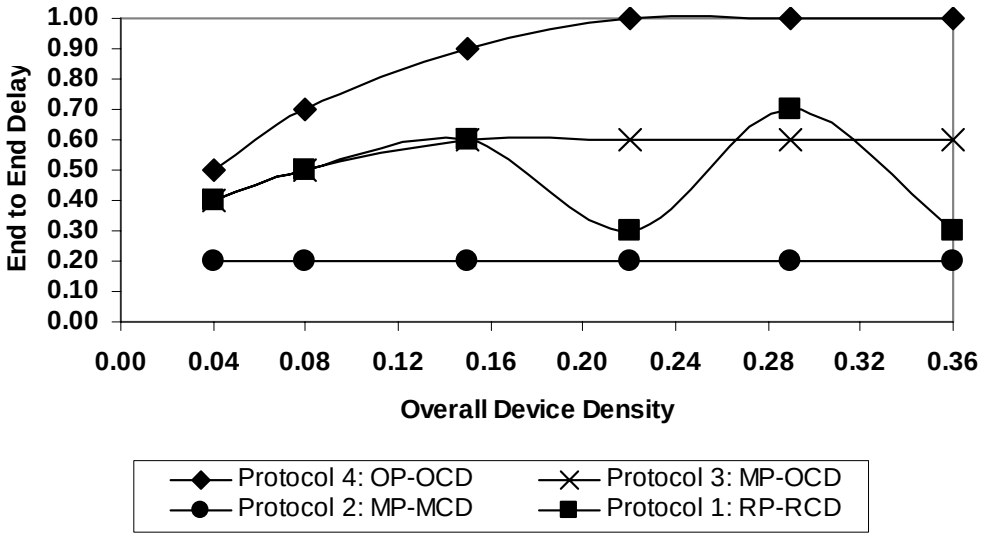


Figure 50: End-End Delays in Clustered Device Distribution (C=1, 30% of PMDs) at System Utilization = 90%

Case 3: Results for Cluster=2, Size = 30% of PMDs, Cluster on Route of Transmission

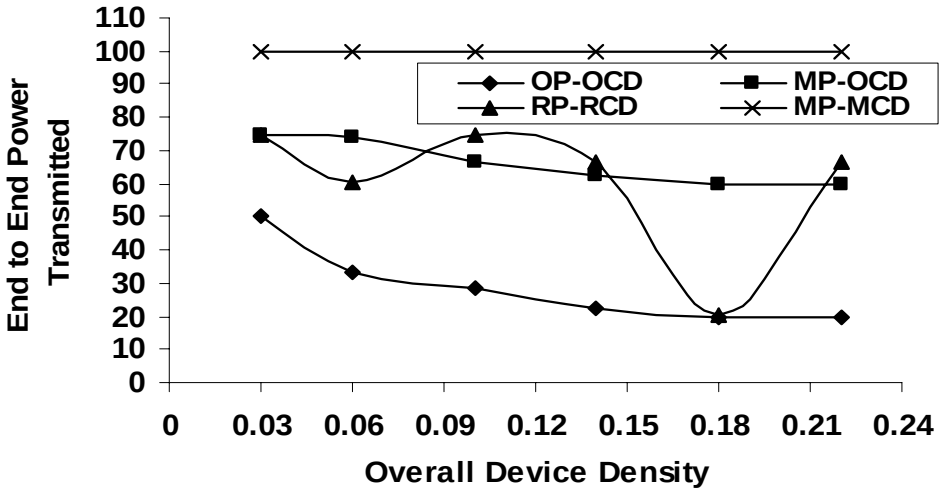


Figure 51: End-End Power Transmitted in Clustered Device Distribution, C=2, 30% of PMD

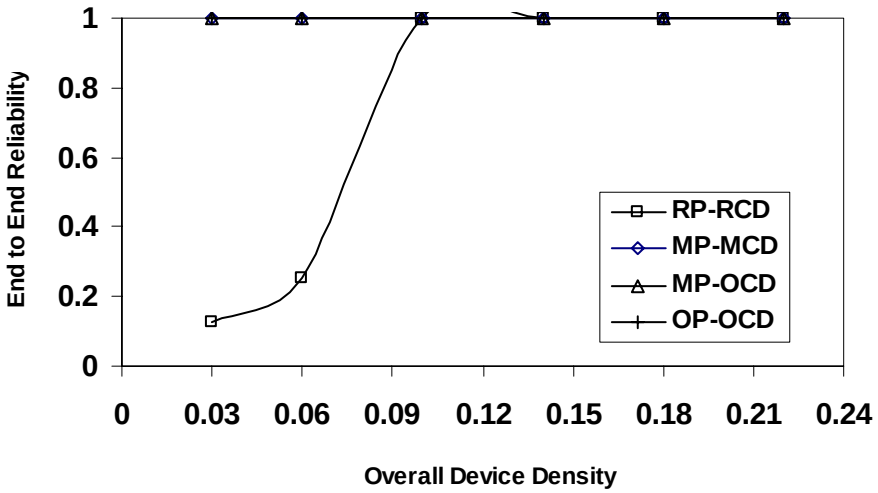


Figure 52: End-End Reliability in Clustered Device Distribution C=2, 30% of PMD

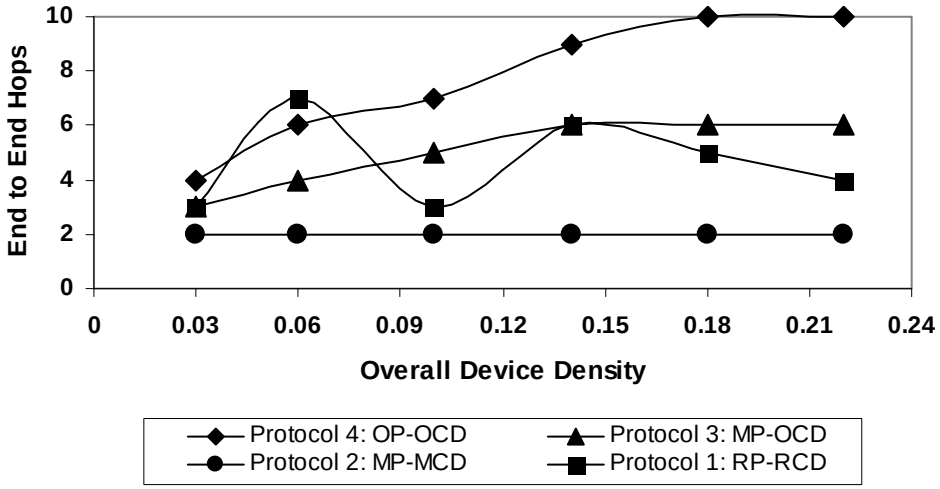


Figure 53: End to End Hops for Uniform Device Distribution, C=2, 30% of PMDs

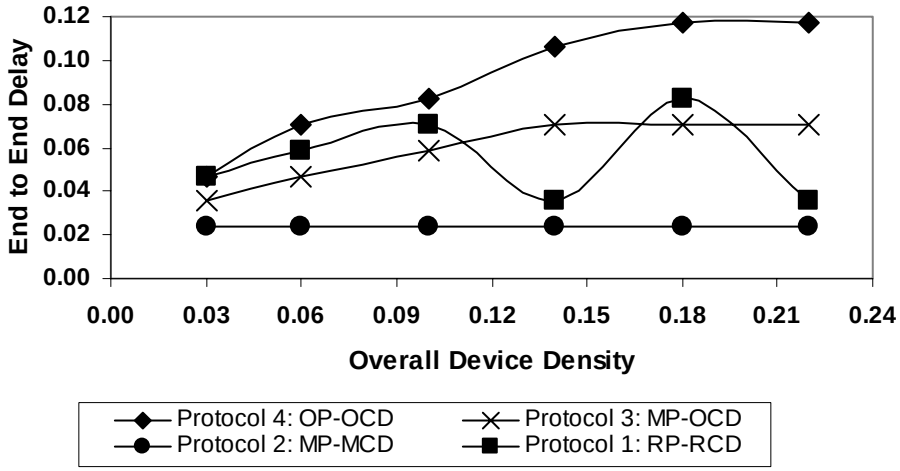


Figure 54: End-End Delays in Clustered Device Distribution (C=2, 30% of PMDs) at System Utilization = 15%

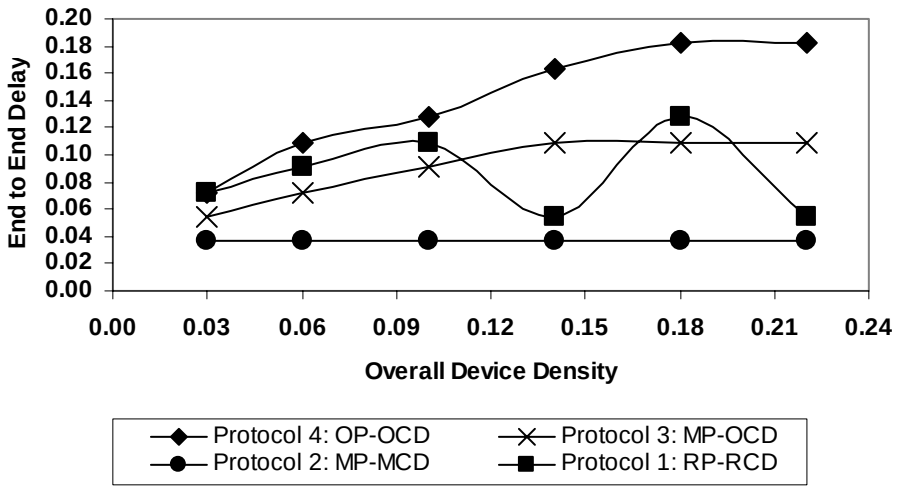


Figure 55: End-End Delays in Clustered Device Distribution (C=2, 30% of PMDs) at System Utilization = 45%

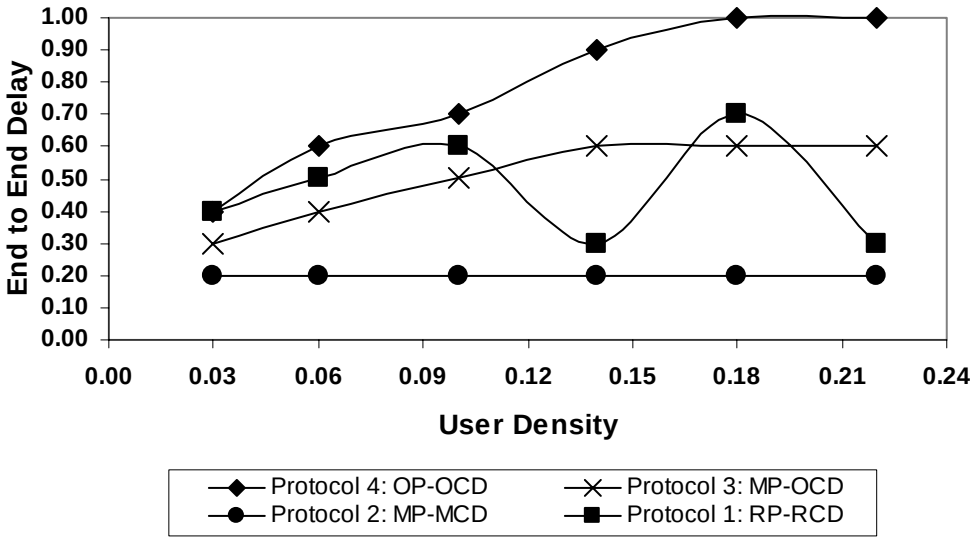


Figure 56: End-End Delays in Clustered Device Distribution (C=2, 30% of PMDs) at System Utilization = 90%

Based on the analytical model and the results of the performance analysis it can be concluded that the PRD protocols meet the desired objectives of enhancing end to end reliability in signal transmission. The performance of end to end power consumption and delays further substantiate the utility and effectiveness of the PM-PRD scheme in allocating PRD protocols and/or sleep strategy for diverse patient monitoring scenarios such that power usage is optimized and end to end reliability is maximized at acceptable delays.

CHAPTER 7

CONLUSION AND FUTURE RESEARCH

Healthcare sector around the world is facing a crisis due to exponential rise in healthcare costs. Epidemiological data validates that a large portion of the healthcare expenses are associated with mismanagement of chronic illnesses and corresponding lack of comprehensive monitoring of patients. Patient monitoring substantiated by technology has been proposed for enhancing the healthcare services to chronic patients while economizing the human/financial resources of the healthcare sector. Most patient monitoring solutions depend solely on infrastructure-oriented wireless networks for networking support which inherently suffer from unpredictable network coverage. Consequently the quality and dependability of patient monitoring solutions are not completely satisfactory.

Mobile ad hoc network (MANET) can be formed as and when needed with/without the presence of an infrastructure and have the potential of enhancing the networking support of infrastructure-oriented networks when the coverage of latter is limited or non-existent. The availability of mobile monitoring devices with routing and transmitting capabilities have brought to the foreground the potential of leveraging MANETs for enhancing the networking support for patient monitoring solutions. There are colossal promises and challenges associated with utilizing MANETs to support comprehensive patient monitoring solutions. The current study is a novel response to the grand challenge of leveraging MANETs for patient monitoring. Specifically, the current research focuses on efficient utilization of the limited power resources in order to maximize reliability and minimize delays in signal transmission from the source (patient) to the destination (healthcare professional) via a multi-hop MANET. The conflicting nature of efficiency in power consumption while enhancing the performance

of end to end reliability and delays makes the research problem notoriously difficult to operationalize.

The current research utilizes design science research methodology and meets the design science research requirements (Hevner et al. 2004) as summarized in Table 15. The research develops and articulates (a) power management techniques (PRD protocols) that manage transmit power by the source and the intermediate routing PMDs such that end to end reliability is maximized for diverse scenarios at variable end to end delays and power consumption and (b) the PM-PRD scheme that analyzes a given monitoring scenario and operationalizes the power management techniques (PRD protocols and/or sleep strategy) that best meets the requirements/constraints of the scenario. The PM-PRD scheme supplements the PRD protocols to the extent that the latter enhances reliability while the former incorporates the PRD protocols for a given monitoring scenario with the goal to optimize power resources such that reliability is enhanced at the lowest possible delays in end to end signal transmission.

An analytical modeling technique and the corresponding results rigorously demonstrate the utility and effectiveness of the proposed PRD protocols and the corresponding PM-PRD schemes. The performance of the key measures end to end reliability, end to end power consumption, and end to end delays are leveraged for the assessment. Signal transmissions via the PRD protocols consistently validate that 100% reliability can be achieved. The performance analysis of the key measures further substantiate the effectiveness of the PM-PRD scheme in operationalizing the protocols that best meet the requirements/constraints of a monitoring scenario. Thus the results from the study indicate the existence of optimal

conditions that achieve 100% reliability while conserving power at reasonable delays in end to end signal transmission.

Table 15: Mapping Against Design Science Guidelines (Hevner et al. 2004)

Guidelines	Contribution
Design as an Artifact	Design outcomes: Power management techniques (i.e. PRD protocols and Sleep Strategy) and the PM-PRD Scheme
Problem Relevance	Responds to the healthcare crisis by addressing the colossal opportunities and challenge associated with utilizing MANETs for comprehensive patient monitoring
Design Evaluation	Utility and effectiveness of the design artifacts rigorously demonstrated via analytical modeling technique
Research Contributions	Design artifact and extensible analytical model which is by far the first effort to investigate the potential of leveraging MANETs for patient monitoring solutions thereby extending the knowledge base and opening doors for future research and innovation
Research Rigor	Design outcomes and corresponding rigorous evaluation that meet the conflicting research objectives of optimizing resource usage while maximizing reliability at reasonable delays.
Design as a Search Process	Design and development of the research artifacts and analytical model; identifying and incorporating independent variables that create diverse monitoring scenarios; developing key measures
Communication of the Research	Development of technical details of the artifacts and the analytical model for technical researchers; implications, opportunities, and challenges associated with the continuation of the research for the behavioral researchers and practitioners

There are three main results of this research. Firstly, this research demonstrates that it is possible to leverage MANETs formed among PMDs to enhance the network coverage of

existing infrastructure oriented networks and thereby provide dependable patient monitoring solutions. Specifically it highlights that the need to optimize resource usage (i.e. battery power) and enhance reliability at reasonable delays for end to end signal transmission with respect to patient monitoring solutions. Although the underlying bases of MANETs and the proposed power management techniques (variable rate transmit power and sleep mode) have been articulated, the corresponding context specific protocols and scheme that address the requirements/constraints of patient monitoring applications via key independent and dependent variables do not exist. The research meets several key requirements and constraints including diverse monitoring (alert, periodic, continuous), reliability, delays, power usage, patient mobility, and routine/emergency message transmissions. It is possible to extend the research to support applications in other domains in which reliability, delays, power usage are critical requirements such as applications pertaining to defense etc.

Secondly, this research is the first effort to the best of my knowledge to investigate the unsheltered territory of applying MANETs in the context of healthcare which has strict constraints and requires highly regulated, reliable, and secure applications. The research not only delves and assesses the obscure and protected requirements of the patient monitoring but also maps the key requirements to specific challenges/constraints associated with utilizing MANETs for patient monitoring. The current research explores an alternative solution to allowing the aging population to lead an independent life outside of the hospitals while being comprehensively monitored for detection of anomalies. The use of MANET is an alternative cost-efficient means to increasing network coverage by extending the infrastructure.

Thirdly, the analytical model developed in this research is extensible and allows for future research to leverage the model for validating the results of the current research. Alternatively, the solution presented in the current research can also be extended and the utility can be assessed in comparison to other future innovations.

There are several limitations of the current research which can be addressed in future research efforts. The current research is a novel effort to utilizing MANETs for patient monitoring applications. The solution proposed needs to be expanded to address other key requirements of patient monitoring applications such as: security, scalability, routing, and applicability to diverse settings. The solution can also be extended to other domains and the applicability be evaluated. Further extensive testing of the proposed solutions needs to be undertaken under diverse scenarios and settings such as: utilizing cooperative/non-cooperative patient monitoring devices in the area of transmission and utilizing dynamic route changes in a MANET, utilizing a hybrid network (MANET + Infrastructure oriented networks) for end to end signal transmission. Comparative evaluation of the proposed power management techniques with other techniques would enhance the level of confidence in the current and future research. Contingent on availability of resources a working prototype can be created and evaluated. The case study utilized for validation assumes a pure MANET for end to end signal transmission, future studies are warranted to extend the validation to a hybrid network involving assymetrical devices with dynamic route changes.

Additionally further research is warranted to understand the economic implications in terms of cost-benefit analysis for the usage of MANETs. Moreover adoption issues pertaining to patients using MANETs to transmit protected health information to a healthcare professional via other PMDs is a sensitive topic and needs to be assessed. Healthcare sector has been

known to have the biggest inertia to changing the practice of healthcare. Besides healthcare is one of the most regulated industries. Hence the utility of the proposed solution will largely depend on patients' adoption criteria and their relative confidence in the privacy and security of the system. Nonetheless it is imperative to address these concerns via future research activities.

Despite of the limitations of the current research and the need to extend the work in future research this research has the potential of being a harbinger of much needed innovation in healthcare delivery and practice specifically pertaining to dependable patient monitoring solutions outside of the hospitals. Future research will confirm or refute the proposals made in the current research and lead to new strategies that can be implemented to cope with the healthcare crisis.

APPENDIX A: FORMAL EXPRESSIONS/ALGORITHM OF THE PM-PRD SCHEME

Table 15: Algorithm for Process1-Task 1

Process1-Task 1: Analyze Patient's Vital Signs
OBTAIN VITAL SIGNS (AT PRESPECIFIED INTERVALS) ANALYZE CURRENT READINGS AGAINST PRIOR STORED READINGS If the current readings > Threshold Readings OR If the current readings < Threshold Readings Alert Detected = True Alert Transmitted = False CATEGORIZE ALERTS If Anomalous Reading is > X points above Threshold Reading ALERT = EMERGENCY Else ALERT = ROUTINE

Table 16: Algorithm for Process1-Task 2

Process1-Task 2: Analyze Patient's Environment
ANALYZE OVERALL DEVICE DENSITY (ODD) AND PRESENCE OF CLUSTERS If Overall Device Density (ODD) in Transmission area >= Threshold Device Density (TDD) ODD = High Else ODD = Low ANALYZE BATTERY POWER LEVEL (BPL) OF THE PMD If BPL >= Threshold Battery Power (TBP) BPL = High Else BPL = Low

Table 17: Algorithm for Process1-Task 3

Task 6: Assess the Applicability of Sleep Strategy Process1-Task 3: Analyze Battery Power
ANALYZE BATTERY POWER LEVEL (BPL) OF THE PMD If BPL >= Threshold Battery Power (TBP) BPL = High Else BPL = Low

Table 18: Algorithm for Signal Transmission Based on MANET for Patient Monitoring

Process3-*Task 7: T*ransmissions based on PM-PRD Scheme

IF AN ANOMALY IS DETECTED AND TRANSMISSION IS WARRANTED

```
If Alert Transmitted = False AND If Alert = Emergency
        ANALYZE OVERALL DEVICE DENSITY (ODD) AND PRESENCE OF CLUSTERS
        If Overall Device Density (ODD) in Transmission area >= Threshold Device Density (TDD)
                If there are No Clusters Detected in Transmission area //Uniform Distribution//
                ANALYZE BATTERY POWER LEVEL (BPL) OF THE PMD
                        If BPL >= Threshold Battery Power (TBP)
                                INVOKE PRD PROTOCOL MP-OCD
                        Else    INVOKE PRD PROTOCOL RP-RCD
                Else // Clustered Distribution//  INVOKE PRD PROTOCOL MP-MCD
        Alert Transmitted = True

If Alert Transmitted = False AND If Alert = Routine
        ANALYZE OVERALL DEVICE DENSITY (ODD) AND PRESENCE OF CLUSTERS
        If Overall Device Density (ODD) in Transmission area >= Threshold Device Density (TDD)
                If there are No Clusters Detected in Transmission area //Uniform Distribution//
                ANALYZE BATTERY POWER LEVEL (BPL) OF THE PMD
                        If BPL >= Threshold Battery Power (TBP)
                                INVOKE PRD PROTOCOL OP-OCD
                        Else    INVOKE PRD PROTOCOL RP-RCD
                Else // Clustered Distribution //   INVOKE PRD PROTOCOL MP-OCD
        Alert Transmitted = True
```

Table 19: Algorithm for Process3-Task 6

Process 3: Task 6: Assess the Applicability of Sleep Strategy
INVOKE SLEEP STRATEGY IF NO ANOMALIES DETECTED ANALYZE OVERALL DEVICE DENSITY (ODD) AND PRESENCE OF CLUSTERS If Overall Device Density (ODD) in Transmission area >= Threshold Device Density (TDD) If there are No Clusters Detected in Transmission area //Uniform Distribution// PMD transitions to Sleep Mode for the duration of the "Idle State" Else If the PMD is in a Cluster //Clustered Distribution - PMD in the Cluster// PMD transitions to Sleep Mode during the "Idle State" Else PMD Listens/Routes Transmitted Signal //PMD not in the Cluster// //Since Sleep Strategy Requirements are Violated//

Table 20: Algorithm for PRD Protocols

Invoking the PRD Protocols
INVOKE PRD PROTOCOL MP-MCD Transmit Signal = MP-MCD PMD Transmit Signal = Maximum Power Level of the PMD IMD (Intermediate Monitoring Device) Transmit Signal = Maximum Power Level If BPL of IMD <= TBP for supporting Maximum Power Level Transmission at the particular node=RP-RCD //Random Power Level from the Available Power// INVOKE PRD PROTOCOL MP-OCD Transmit Signal = MP-OCD PMD Transmit Signal = Maximum Power Level of the PMD IMD (Intermediate Monitoring Device) Transmit Signal = Optimal Power Level Optimal Power Level = Minimal Power Level to Transmit a Signal to the Next Node //Derived Based on Listening to Prior Transmissions – Largely Dependent on Device Density// If BPL of IMD <= TBP for supporting Optimal Power Level

Transmission at the particular node=RP-RCD //Random Power Level from the Available Power//

INVOKE PRD PROTOCOL OP-OCD
Transmit Signal = OP-OCD
PMD Transmit Signal = Optimal Power Level of the PMD
IMD (Intermediate Monitoring Device) Transmit Signal = Optimal Power Level
Optimal Power Level = Minimal Power Level to Transmit a Signal to the Next Node
//Derived Based on Listening to Prior Transmissions – Largely Dependent on Device Density//
If BPL of IMD <= TBP for supporting Optimal Power Level
Transmission at the particular node=RP-RCD //Random Power Level from the Available Power//

INVOKE PRD PROTOCOL RP-RCD
Transmit Signal = OP-OCD
Random Power Level = A random power level from the available power level of the PMD
PMD Transmit Signal = Random Power Level
IMD (Intermediate Monitoring Device) Transmit Signal = Random Power Level

GLOSSARY OF TERMS AND ABBREVIATIONS

- MANET - Mobile ad hoc network: A mobile ad hoc network consists of a collection of geographically distributed wireless devices or nodes that can dynamically form a network without a pre-defined infrastructure and communicate with one another over a wireless medium. The nodes act as routers as well as transmitters.
- Source: The patient monitoring device intiating the signal transmission
- Destination: A healthcare professional's device to which the signal is transmitted to form the source
- End to End Signal Transmission: Transmission from the source to the destination
- PMD: Patient Monitoring Device
- Transmitted Power: Power transmitted by each PMD at each hop in the end to end signal transmission
- Device Range: The range of the transmitting PMD which is dependent on transmitted power at each hop
- Number of End to End Hops: Total number of hops in end to end signal transmission
- Uniform Device Distribution: PMDs distributed uniformly in the area of transmission
- Clustered Device Distribution: Patient mobility resulting in non-uniform distribution of PMDs in the area of transmission
- Variation in Size of Clusters: The clusters vary in size (i.e. the number of PMDs forming the cluster)
- Variation in Number of Clusters: The clusters can vary in number (i.e. the number of clusters in the area of transmission)

- Clusters On/Off the Route of Transmission: Clusters can be on route and off route of end to end signal transmission
- Overall Device Density/ Overall Network Density: The density of PMDs in the area of transmission, some or all of which can route/transmit signal via a multi-hop MANET
- System Utilization: System utilization defines the transmission load on the system.
- Service Rate: Service rate is specific to the PMD and defines the rate at which a signal is processed by a PMD
- End to End Power Transmitted: Total power consumed in end to end signal transmission via a multi-hop MANET
- End to End Reliability: Reliability in end to end signal transmission meausred in terms of probability of locating cooperative PMDs at each hop in end to end transmission
- End to End Delays: Total delays in end to end signal transmission.
- PRD: Power-Reliability-Delays
- PRD Protocol: Power management protocols designed to manage the transmitted power by the source and the intermediate routing devices with the objective to maximize end to end reliability for diverse monitoring scenarios
- RP-RCD: Random power level transmitted from the source and intermediate routing devices in end to end signal transmission
- MP-MCD: Maximum power level transmitted from the source and intermediate routing devices in end to end signal transmission

- MP-OCD: Maximum power level transmitted from the source and optimum power level transmitted from the intermediate routing devices in end to end signal transmission
- OP-OCD: Optimum power level transmitted from the source and the intermediate routing devices in end to end signal transmission
- Optimum Power Level: Minimal transmitted power level to reach the next node with maximum reliability
- PM-PRD: Patient Monitoring via MANET focusing on Power-Reliability-Delays
- PM-PRD Scheme: A scheme that assesses a patient monitoring scenario and operationalizes a PRD protocol that best meets the requirements and constraints of the patient monitoring scenario
- Analytical Modeling Technique: Methodology employed for evaluation of the research artifacts. It entails deriving a mathematical model of the real system via analytical expressions representing diverse scenarios of interest and the relationship between the independent and the dependent variables
- Cooperative Routers: The patient monitoring device(s) located within the range of a signal transmission are assumed to be able and willing to route/transmit the signal forward via a multi-hop MANET till the signal reaches the destination.

REFERENCES

Kern, S. E and Jaron, D. (2003) Healthcare Technology, Economics and Policy: An Evolving Balance, IEEE Engineering in Medicine and Biology Magazine, 22, 1, 16-19.

Tablado, A., Illarramendi A., Bermudez J., Goni A. (2003) Intelligent Monitoring of Elderly People; In Proc. 4th Annual IEEE Conf. On Information Technology Applications in Biomedicine, UK.

US Administration on Aging Report on Demographic Changes, http://www.aoa.dhhs.gov/aoa/stats/aging21/demography.html

Kunze, C., Grobmann, U., Stork, W., Muller-Gaser, K.D., Applications of Ubiquitous Computing in Personal Health Monitoring Systems, http://www-lih.univ-lehavre.fr/~hogie/bib/Ubiquitous%20computing/Application%20Of%20Ubiquitous%20Computing%20In%20Personal%20Health%20Monitoring%20Systems.pdf

Varshney, U. Using Wireless Networks for Enhanced Monitoring of Patients. In Proc. of Americas Conference on Information Systems (AMCIS), 2004

Varshney, U. Pervasive Healthcare: Applications, Challenges and Wireless Solutions. Communications of the Association of Information Systems. Vol.16, 2005

Boult, C. et al., Innovative Healthcare for Chronically Ill Older Persons: Results of a National Survey, The American Journal of Managed Care, September 1999

Chronic Care Improvement, ITAA E-Health White Paper: A Product of the E-health Committee.

Hunter, D. J., Disease Management: Has it a Future, www.bmj.com , Vol. 320, February 2000.

Vaishnavi, V. and Kuechler, W., Design Research in Information Systems, Atlanta GA 2004

Hevner, A., March, S., and Ram, S., Design Science in Information Systems Research, MIS Quarterly Vol. 28, No. 1, 2004, pp 50-57

Vaishnavi, V. and Kuechler, W., Design Research in Information Systems, Atlanta GA 2004

Gieras, I. A. (2003) The proliferation of patient-worn wireless telemetry technologies within the U.S. healthcare environment, Proceedings of 4th International IEEE EMBS Special Topic Conference on Information Technology Applications in Biomedicine, 295-298.

Goldberg, S. and Wickramasinghe, N. (2003) 21st Century Healthcare-The Wireless Panacea, In Proceedings of the 36th Hawaii International Conference on System Sciences

Gouaux, F., Simon-Chautemps L., Adami S., Arzi M., et.al; (2003) Smart Devices for the Early Detection and Interpretation of Cardiological Syndromes, In Proc. 4th Annual IEEE Conf. On Information Technology Applications in Biomedicine, UK.

Hung, K. and Zhang, Y. (2003). Implementation of a WAP-Based Telemedicine System for Patient Monitoring, IEEE transactions on Information Technology in BioMedicine, Vol. 7 No. 2, June 2003

Istepanian, R. S. H. and Petrosian, A. A. (2000) Optimal Zonal Wavelet-based ECG Data Compression for a Mobile Telecardiology System, IEEE Transactions on Information Technology in Biomedicine, 4, 3, pp. 200-211, Sept.

Jovanov. E., O'Donnel. A., Morgan. A., Priddy B., Hormigo. R., (2002) Prolonged telemetric monitoring of heart rate variability using wireless intelligent sensors and a mobile gateway, In Proc. of the Second Joint IEEE EMBS/BMES Conference, 2002 (24th Annual EMBS Conference and the Annual Fall Meeting of the Biomedical Engineering Society), 1875-1876.

Jovanov, E., O'Donnell Lords, A., Raskovic, D., Cox, P. G., Adhami, R. and Andrasik, F. (2003) Stress Monitoring using a Distributed Wireless Intelligent Sensor System, IEEE Engineering in Medicine and Biology Magazine, 22, 3, May-June, pp. 49-55

Kafeza, E., Chiu, D. K. W., Cheung, S. C. and Kafeza, M. (2004) Alerts in Mobile Healthcare Applications: Requirements and Pilot Study, IEEE Transactions on Information Technologies in Biomedicine, 8, 2, pp. 173-181.

Kara, A. (2001) Protecting Privacy in Remote-Patient Monitoring, IEEE Computer, 34, 5, 24-27.

Kern, S. E and Jaron, D. (2003) Healthcare Technology, Economics and Policy: An Evolving Balance, IEEE Engineering in Medicine and Biology Magazine, 22, 1, 16-19.

Khoor, S., Nieberl, K., Fugedi, K., Kail, E. (2001) Telemedicine ECG-telemetry with Bluetooth Technology, In Proc. Computers in Cardiology 2001, Rotterdam, 585-588.

Kyu J. C. and Asada, H. H. (2002) Wireless, Battery-less Stethoscope for Wearable Health Monitoring, In Proc. the IEEE 28th Annual Northeast Bioengineering Conference, Philadelphia, PA, 187-188.

LifeSync – www.wirelessecg.com, 2005

Liszka, K. J., Mackin, M. A., Lichter, M. J., York, D. W., Pillai, D., and Rosenbaum, D. S. (2004) Keeping a Beat on the Heart, IEEE Pervasive Computing, October-December, pp. 42-49.

Lymberis, A. (2003) Smart Wearables for Remote Health Monitoring, from Prevention to Rehabilitation: Current R&D, Future challenges, Proceedings of 4th International IEEE EMBS Special Topic Conference on Information Technology Applications in Biomedicine, 272 – 275.

Coile, R.C. and Trusko, B.E., Healthcare 2020: Technology in the New Millennium, Health Management Technology, www.healthmgttech.com, December 1999

Dishman, E. Inventing Wellness Systems for Aging in Place. IEEE Computer Vol. 37. May 2004.

Korhonen, I. et al. Health Monitoring in the Home of the Future: Infrastructure and Usage Models for Wearable Sensors. IEEE Engineering Medicine and Biology Magazine. Vol. 22, May/June 2003

IOM. To Err is Human: Building a Safer Health System, US Institute of Medicine Report. http://www.nap.edu/books/0309068371/html/

Stanford, V. Using Pervasive Computing to Deliver Elder Care. IEEE Pervasive Computing Magazine, Jan-March 2002, pp. 10-13

Website for Gator Tech Smart House: http://www.icta.ufl.edu/gt.htm

Website for Smart Shirt: http://www.smartshirt.gatech.edu

Website for TV-based Monitoring by Philips (http://www.medical.philips.com/main/news/content/file_630.html)

Website for Patient Monitoring by Welch Allyn (http://www.monitoring.welchallyn.com/products/wireless/

Suzuki, T. and Doi, M. (2001) LifeMinder: An Evidence-Based Wearable Healthcare Assistant, Proceedings of the ACM CHI Conference

Sneha et al. Wireless ECG Monitoring System for Pervasive Healthcare. In Proc. of the eleventh Americas Conference on Information Systems, August 2005, Omaha NE

Website for Cardionet. http://cardionet.com/

Jalal et al. Secure smart homes using Jini and UIUC SESAME. Proc. of Annual Computer Society Application 2000

Michael J. Covington, Securing Context-Aware applications using environment roles. In Symp. On Access Control Model and Technology, May 2000

McGee, M.K. E-Health on the Horizon, Informationweek.com, May 17th 2004.

Doherty, G. B. et al. The effectiveness of an interactive electronic lung function monitoring system in the total management of refractory asthma. Disease Manage Health Outcomes, Vol. 3 No. 2.

Sarela, A. et al. IST Vivago – an intelligent social and remote wellness monitoring system for the elderly. In Proc. of the 4th Annual IEEE EMBS Special Topics Conf. Information Technology Application in Biomedicine (ITAB 2003). April 2003.

UbiHealth: 2nd International Workshop on Ubiquitous Computing for Pervasive Healthcare Applications. http://www.healthcare.pervasive.dk/ubicomp2003/

Singh, S., Woo. M. and Raghavendra, C.S., "Power Aware Routing in Mobile Ad Hoc Networks", In Proc. of ACM MobiCom Conference, 1998

Gomez, J. et al. "PARO: Supporting Dynamic Power Control Routing in Wireless Ad Hoc Networks", ACM/Kluwer Journal of Wireless Networks, Vol. 9, No. 5, 2003

Rodoplu, V., and Meng, T. "Minimum Energy Mobile Wireless Networks", IEEE JSAC, Vol. 17, No. 8, August 1999

W. Lou and J. Wu, "A Reliable Broadcast Algorithm with Selected Acknowledgements in Mobile Ad Hoc Networks", IEEE Globecom, August 2003.

J. M. Kim and Y. I. Eom, "An Adaptive Routing Protocol for Supporting Reliable Communication in Wireless Ad-Hoc Network Environments", In Proc. IEEE Pacific Rim Int. Symp. on Dependable Computing, 2001

S. Y. Cho, J. H. Sin and B. I. Mun, "Reliable Broadcast Scheme Initiated by Receiver In Ad Hoc Networks", In Proc. of the 28th Annual IEEE International Conference on Local Computer Networks (LCN), Nov. 2003

T. Camp, J. Boleng, and, V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research", Wireless Communications and Mobile Computing (WCMC), vol. 2, no. 5, pp. 483-502, 2002

S. Jain, "Energy Aware Communication in Ad-hoc Networks", Technical Report UW-CSE March 2003 (University of Washington, Seattle)

Wattenhofer, R. et al. "Distributed Topology Control for Power Efficient Operation in Multi-hop Wireless Ad Hoc Networks", In Proc. of IEEE INFOCOM Conference, 2001

Kwon, T.J. and Gerla, M., "Clustering with Power Control", In Proc. of IEEE MILCOM Conference, 1999

Kawadia, V. and Kumar, P. R., "Power Control and Clustering in Ad Hoc Networks", In Proc. of IEEE INFOCOM Conference, 2003

Reddy et al., A review of QOS Research in MANETs, IEEE Transactions in Mobile Computing 2006

Vaidya, N.H., "Open Problems in Mobile Ad Hoc Networking", PowerPoint slides Keynote talk presented at the Workshop on Local Area Networks, November 14, 2001, Tampa, Florida (in conjunction with 26th Conference on Local Computer Networks).

Vaidya, N.H., "Tutorial on Mobile Ad Hoc Networks: Routing, MAC and Transport Issues", Infocom 2006 version of the tutorial.

W. Stallings, Wireless Communications and Networks, First edition, Prentice Hall, NJ, 2002

J. Zhu and S. Papavassiliou, "On the Connectivity Modeling and the Tradeoffs between Reliability and Energy Efficiency in Large Scale Wireless Sensor Networks", In Proc. IEEE WCNC, March 2003

M. Chiasson, E. Davidson,, et al., Strangers in a Strange Land: Can IS Meet the Challenges and Opportunities of Research in Healthcare, Proceedings of the Tenth Americas Conference in Information Systems (AMCIS) (2004).

Alisha D. Malloy, Design and Performance Evaluation of QOS-Oriented Wireless Networks, CIS Doctoral Dissertation, July 2002

Punit Ahluwalia, A Study of the QOS in Group Oriented Mobile Transactions, CIS Doctoral Dissertation, July 2006