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A framework for enabling patient monitoring via mobile ad hoc network

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ABSTRACT

A critical component of comprehensive patient monitoring is reliability in communication between the patients and the healthcare professionals without any time and location dependencies. Patient monitoring applications largely rely on infrastructure based wireless networks for signal transmission. However, infrastructure based wireless networks till date, suffer from unpredictable network coverage and have thus been attributed to the unpredictable communication reliability of patient monitoring applications. This research investigates an approach based on leveraging mobile ad hoc network to address the challenge of enhancing communication reliability in the context of patient monitoring. Mobile ad hoc network, formed among patient monitoring devices, has the potential of enhancing network coverage and enabling signal transmission from an area which has low or non-existent coverage from infrastructure based networks. In order to utilize mobile ad hoc network in the context of patient monitoring we propose (1) power management protocols that address the challenge of managing the low battery power of patient monitoring devices while maximizing communication reliability and (2) a framework that models the complex decision logic involved in leveraging mobile ad hoc network for diverse patient monitoring scenarios. Analytical evaluation of the proposed approach supports the premise that mobile ad hoc network formed among patient monitoring devices can enhance the reliability of signal transmission thereby improving the quality of patient monitoring applications. Technical and managerial implications of the research findings and the direction of future research are discussed.

1. Introduction

Healthcare systems around the globe are experiencing an exponential rise in aging population (expected to reach 761 million by 2025) followed by a corresponding rise in healthcare expenses (projected to reach 20% of the GNP by 2015 for US) and heavy utilization of healthcare services [5,10,15,50,53]. Comprehensive patient monitoring enabled by information communication technologies is widely recognized as an effective tool in containing healthcare expenses, efficiently managing chronic diseases, reducing complications and unnecessary hospitalizations, and facilitating efficient delivery of a wider range of medical services by the healthcare professionals [8,17,62]. Yet concerns with reliable communication in the context of patient monitoring have been highlighted [15,50,56,57,62]. The sole reliance of patient monitoring applications on infrastructure based wireless networks (which inherently suffer from unpredictable spotty coverage) for transmission has largely been attributed to the incumbent volatility in signal transmission, unreliability in communication, and opportunistic security threats by malicious agents [33]. In the current research we investigate the viability of utilizing mobile ad hoc network to *augment* the coverage of infrastructure based networks with the *objective* to enhance communication reliability of patient monitoring solutions.

Consider the following case of patient monitoring supported by infrastructure oriented wireless network followed by a proposed approach utilizing mobile ad hoc network (Fig. 1). *Patient "X" resides in a nursing home. A device continuously monitors/analyzes his vital signs and wirelessly transmits alerts when an anomaly is detected. A WLAN — an infrastructure-based wireless network, supports alert transmissions. At 9:00 am a nurse making a routine visit, found "X" dead in the restroom. Later investigation revealed that the monitoring device detected an anomaly in the vital signs and made several attempts to transmit the alert. Unfortunately, the transmission failed due to no network in the restroom.*

The proposed solution to the preceding fatal case leverages mobile ad hoc network, formed among patient monitoring devices, to transmit the emergency alert from the area where the coverage from the existing infrastructure based network is low and/or non-existent (Fig. 1). *In the absence of wireless coverage in the restroom, the patient's monitoring device "X" forms an* ad hoc *network with the other nearby devices, "F" and "A". The alert is transmitted to the nurse "Y"* via *multiple hops (X–A–B–C–D–E–Y)* (Fig. 1). *The nurse was able to provide pertinent*

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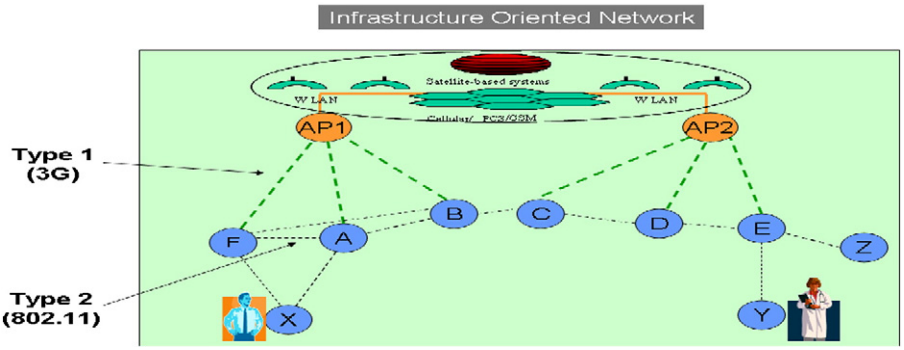

Fig. 1. Signal transmission from "X" to "Y" via mobile ad hoc network.

medical attention to "X" and thus a fatal outcome was evaded. The proposed approach doesn't seek to replace the infrastructure based wireless network(s); it merely proposes to supplement the coverage of infrastructure based wireless network(s) by mobile ad hoc network when the coverage from the former is low or non-existent.

The current research is based on the premise that in order to support comprehensive monitoring of patients involving transmission of emergency alerts, ensuring reliable end to end communication is a critical requirement. Mobile ad hoc network affords the possibility of enhancing communication reliability in an event when an alert needs to be transmitted from an area with low/non-existent coverage from an infrastructure based network [50,57–60]. The current research is among the first to tackle the rich problem space of numerous opportunities and challenges associated with leveraging mobile ad hoc network in the context of patient monitoring. Based on this premise, we address the following research question: "*How can mobile* ad hoc *network be leveraged to maximize communication reliability while optimizing the limited battery power of the patient monitoring devices at minimal delays for diverse monitoring scenarios*"*?* We utilize a multifold approach grounded in the unique characteristics of patient monitoring domain to handle the aforementioned research question. The specific research objectives include: (a) investigation of the opportunities and challenges of utilizing mobile ad hoc network for comprehensive patient monitoring, (b) assessment of the various elements that facilitate the development of an integrated framework modeling the complex decision logic of optimizing the limited battery power of the monitoring devices while maximizing reliable end to end communication at minimal delays in diverse patient monitoring scenarios, (c) develop protocols to manage the battery power of the patient monitoring devices such that 100% reliability in end to end communication can be achieved, (d) analytical validation of the proposed approach hypothesizing that mobile ad hoc network can enhance communication reliability in the context of patient monitoring. The results validate the utility of the proposed power management protocols in achieving 100% reliability at minimal delays and are likely to open multiple avenues of future research pertaining to the research and practice of patient monitoring.

The remainder of the paper is structured as follows. Section 2 provides background on prior research in patient monitoring and mobile ad hoc network along with discussing unique issues associated with reliability, power management, and delays in the context of mobile ad hoc network for patient monitoring. Section 3 details the proposed (a) power management protocols for managing the low battery power of the patient monitoring devices and (b) framework that integrates the decision logic of utilizing the proposed power management protocols for diverse patient monitoring scenarios with the objective to enhancing reliability while optimizing power usage and delays in the context of leveraging mobile ad hoc network for patient monitoring. Section 4 presents the analytical model and the performance evaluation results of the proposed approach. Section 5 concludes with a discussion of the implications and limitations of the current research followed by the avenues for future research.

2. Background — Patient monitoring and mobile ad hoc networks

The following sections discuss: (a) the requirements, complexities, and current state of research with respect to remote patient monitoring and (b) the challenges/opportunities associated with leveraging mobile ad hoc network in enhancing communication reliability of remote patient monitoring.

2.1. Remote patient monitoring

Remote patient monitoring typically involves: (1) a *Monitoring State* which involves sensing and analyzing disease specific vital signs, and (2) a Transmit State where recorded data is transmitted via a wired/wireless network if an anomaly is detected. Remote monitoring of patients not only has diverse requirements pertaining to the context of monitoring (indoor stationary patient or mobile patients indoor/outdoor), signal transmission (alert based, periodic, or continuous), delay tolerance (higher delay for non-emergency and lower delay for emergency messages) but also spans multiple disease specific parameters such as: duration of monitoring, frequency of data collection and transmission, amount of data transmitted, and nature of monitoring [50]. Moreover, variability in one parameter affects variability in other parameters. For instance: symptoms associated with myocardial infarction can be sensed at least a week before the heart attack hence the application for monitoring heart failure can potentially have a higher delay tolerance whereas an application monitoring critically ill infants may require no delay in alert transmissions. Applications that have higher delay tolerance can withstand slight disruption in connectivity by storing data locally on the monitoring device till the network becomes available for transmission while others with stringent delay requirements may not be able to withstand any disruption in network coverage. Despite the context specific variability associated with the requirements of patient monitoring applications, concerns with reliable communication has been widely highlighted as a key factor impeding the wide-scale utility of comprehensive patient monitoring [50,57–59].

First generation monitoring solutions restricted patient mobility and collected/transmitted data within a hospital via WLANs such as: Micropaq that transmits multi-parametric information via WLANs [64] and LifeSync [31] which uses a short range wireless system (Bluetooth). The next generation monitors collected/transmitted patient's vital signs periodically and allowed patients the flexibility to live at home such as: Medtronic [37], Motiva [66], and CardioNet [65]. Today, it is possible to obtain measurements of heart rate, oxygen saturation, end-tidal CO_2, serum chemistries, and serum glucose via small, non-invasive sensors. Nonin and Numed have developed Bluetooth based wireless vital sign sensors, while Radianse has developed an