Patient Monitoring Using Ad Hoc Wireless Networks: Reliability and Power Management

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ABSTRACT

In the health care domain, a major challenge is how to provide better health care services to an increasing number of people using limited financial and human resources. Wireless patient monitoring has the potential to support these multiple and conflicting requirements. However, the current quality and reliability of patient monitoring have not been very satisfactory due to the unpredictable and spotty coverage of infrastructure-oriented wireless networks. Ad hoc wireless networks can be formed among mobile and wearable patient-monitoring devices for improving the coverage of patient monitoring when infrastructure-oriented networks are not accessible. In this article, we provide support for reliable wireless patient monitoring by presenting several protocols for power management of devices, assisted power control, and sleep strategy. The performance results show that high reliability of message delivery can be obtained while maintaining a level of power conservation.

INTRODUCTION

The increasing cost of health care services, already at 16 percent of the gross national product (GNP) for the United States in 2004 [1], has created several challenges for policy makers, health care providers, hospitals, insurance companies, and patients. A major challenge is how to provide better health care services to an increasing number of people using limited financial and human resources. Wireless telemedicine (including patient monitoring) using increasingly ubiquitous wireless infrastructure is receiving some interest. Examples include a WAP-based telemedicine system [2]; a maritime telemedicine system [3]; telecardiology, teleradiology, and telepsychology [4]; ECG data compression to reduce transmission time over GSM network [5]; and a telemedicine system that can "bring" a specialist doctor to the site of the medical emergency [6].

We envision that future wireless telemedicine will also include monitoring of patients and intervention from health care professionals as and when required. This will reduce the total health care cost, lead to a better utilization of limited health care resources, and will also allow independent living for increasingly older individuals in most countries. In patient monitoring, the following physiological and patient-related conditions need to be monitored: blood pressure, temperature, EKG and pulse, oxygen saturation, skin breakdowns, abnormal gait and balance, motor activity and agitation, current location, cigarette smoke, and the amount of moisture in clothing. The related work includes a hospital-wide mobile monitoring system [7], home monitoring [8], wireless patient monitoring [9], long-term monitoring via wearable devices [10], wireless EEG epilepsy monitoring [11], wireless sensors [12], and wireless patient monitoring [13].

The spotty coverage of existing infrastructure-oriented wireless networks (such as cellular networks and wireless LANs) due to time- and location-dependent channel quality and signal attenuation [14] could lead to an unpredictable quality and reliability of patient monitoring. The resulting delayed medical response to patients could have fatal consequences. To overcome these problems, ad hoc wireless networks can be formed among patients' devices capable of transmitting vital signs over a short-range [9]. Then, using a routing scheme for the ad hoc networks, vital signs can be delivered to one or more health care professionals (Fig. 1).

The use of ad hoc wireless networks for patient monitoring will require reliable delivery of monitoring messages and power management of small and diverse battery-operated devices. Toward these goals, we present several protocols for the power management of devices used for patient monitoring. Many enhancements, including assisted power management combined with the sleep cycle in the routing of vital signs in patient monitoring, are also presented. Based on the performance of the protocols, many interesting observations on the suitability of individual protocols are included. Then, the implications of ad hoc wireless networks for patient monitoring

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and directions for future research are presented.

PATIENT MONITORING REQUIREMENTS AND RELIABILITY ENHANCEMENTS

The requirements of patient monitoring are both diverse (indoor and outdoor, fixed and mobile patients) and complex (the variable length of monitoring, the frequency of signal transmission, and the amount of information). The following are some general requirements of patient monitoring:

Monitoring and transmission of both routine and emergency vital signs: These could include blood pressure, heart rate, temperature, EKG, oxygen saturation, skin breakdowns, abnormal gait and balance, motor activity and agitation, current location, cigarette smoke, and the amount of moisture in clothing. This may involve periodic monitoring/transmission for some vital signs and be event-driven for others.

Reliability of message delivery: Due to potentially life-threatening situations, the reliability of message delivery to health care professionals is the most crucial requirement of patient monitoring. The influencing factors are device range, available power, bit rate, routing protocol, and any failure or uncooperative behavior of other devices.

Message delivery in reasonable time: The network should deliver the messages carrying vital signs within a certain time determined by the level of emergency. The delays could rise substantially under frequent monitoring or for an increased number of monitored patients.

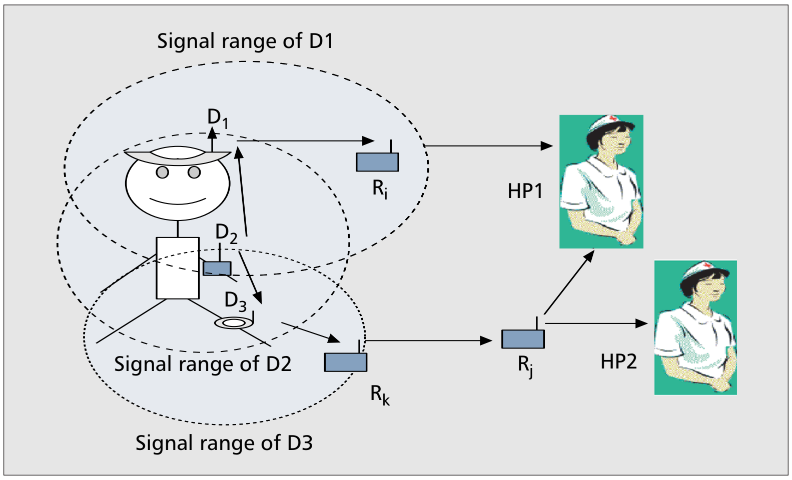
Power conservation: The challenge is to conserve device power while satisfying the reliability requirement of patient monitoring. The influencing factors are the transmitted power required per message, the number of messages that must be routed, and the routing scheme, which can affect both power requirement and reliability.

Coverage for both fixed and mobile patients: Patient mobility could result in an uneven distribution of patients, thus making it difficult to perform reliable patient monitoring. The monitoring support should also cover patients in both indoor as well as outdoor environment.

Support for diverse and battery-limited devices on and around patients: Patient monitoring devices are likely to be very diverse in their functionalities and battery power. These devices must be utilized in terms of power and processing, and must also be matched to the physical conditions of the monitored patients.

Scalability: The patient monitoring network should scale well in terms of the number of patients. The influencing factors are the bit rate, the frequency of monitoring and transmission, and the amount of information per patient. The effective bit rate of an ad hoc network could decrease with an increased distance between devices increases due to

- An increased power requirement exceeding the available device power
- Increased transmission errors requiring retransmission



■ **Figure 1.** *Use of ad hoc networks for patient monitoring.*

- An increased area where no other devices can transmit until the current transmission is successfully completed.

Manageable cognitive load for health care professionals: The patient monitoring system should not overwhelm health care professionals with a large number of monitoring messages. The computational capabilities of the devices need to be utilized to make intelligent decisions about the patient condition and alerting the health care professional only when an anomaly or emergency is detected.

Confidentiality and privacy: As health care information is being transmitted over wireless networks, efforts should be made to keep it confidential and private. This is expected to be the most critical requirements for health care administrators and government regulators.

RELIABILITY AND POWER CONSERVATION PROTOCOLS

In ad hoc wireless networks, reliability of message delivery and power conservation are somewhat conflicting goals. For example, a higher end-to-end reliability for message delivery can be achieved with increased power (or fewer hops), as it increases the chance of finding another node for continued routing [15]. End-to-end reliability for patient monitoring can also be improved by multiple retransmissions, broadcast-based routing, multiple ad hoc networks, and deployment of an increased number of cooperative devices for routing messages [13]. Multiple retransmissions combined with Acknowledgments can increase the reliability of transmissions to the next hop, but with higher transmitted power and an increased traffic. Broadcast routing and the use of multiple ad hoc networks can increase the end-to-end reliability of message delivery, but also result in significant network traffic. The reliability of patient monitoring could also be enhanced by increasing the number of cooperating devices (by offering incentives for routing) and via transmission of the differential value of vital signs in order to reduce network traffic. The differential vital signs can be obtained by utilizing the computational power

Protocol	Level of reliability	Power efficiency	Number of hops	Processing requirements	Suitable for
MP-MCD	Highest (due to maximum power transmission)	Low (battery may not last long as maximum power is continuously transmitted)	Fewest (due to maximum power)	None (all devices transmit at maximum power levels)	Transmission of emergency vital signs
OP-OCD	High (especially for low device mobility)	Highest	Highest (due to minimal power transmission)	Very high (determining optimal power levels)	Transmission of routine vital signs
MP-OCD	Higher (the maximum power from the source device can increase the probability of finding next hop	High level of power conservation possible	More than MP-MCD but less than OP-OCD	High (determining optimal power levels for most devices)	Transmission of low emergency vital signs
RP-RCD	Unpredictable (based on the power level in individual hops)	Unpredictable (based on the sum of all power levels)	Unpredictable (based on the power level in individual hops)	Low (all devices still have to choose a random power level)	N/A

■ **Table 1.** *Protocols for power management.*

of the transmitting devices, which could also lead to a reduced cognitive overload for health care professionals.

The level of transmitted power influences both the ability of a patient's device to locate a cooperating device and the ability of cooperating devices to locate next-hops in ad hoc networks for continued routing. Consequently, the connectivity of the ad hoc network to a large extent depends on the transmitted power. As most patient monitoring devices are battery operated, power management becomes an important requirement in ad hoc networks-based patient monitoring. Ideally, a patient monitoring device should transmit just enough power to reach the next cooperating device. Power management should address conserving individual as well as total power of all devices in the ad hoc network, since the network connectivity and the life of the network both depend on available power. Individual patient devices can either be informed of the amount of power necessary to reach to the next-hop or devices can derive the power levels by using the knowledge from prior transmissions and/or receptions from the neighboring hops. In addition, ad-hoc networks can be formed on-demand to conserve power; however, the decision to create an ad hoc network reactively on-demand or proactively will also depend on the frequency of transmission, the number of patients, and the overhead in maintaining/updating ad hoc network routes. Also, if the number of users (or available power) drops below a threshold, the ad hoc network could be disassociated for saving power.

PROTOCOLS FOR POWER MANAGEMENT

The power management considerations are:
- Providing high levels of reliability for message delivery
- Managing device power
- Matching the protocols' complexity to the device functionalities
- Minimizing the information transmitted from a patient's device

Some of these are used in the design of four protocols for power management as follows.

Maximum Power from Patient's Device and Cooperating Devices (MP-MCD) — Due to a higher probability of finding another node for continued routing, MP-MCD can lead to very high reliability of message delivery. Due to the excess power transmission, routing of messages will involve fewer hops and the total processing and routing load could also be lower. The protocol is also less sensitive to node mobility, as the transmitted power is always at the maximum level. MP-MCD is suitable for emergency messages, and may perform well under low device density, where a higher transmitted power is required to reach a neighboring node.

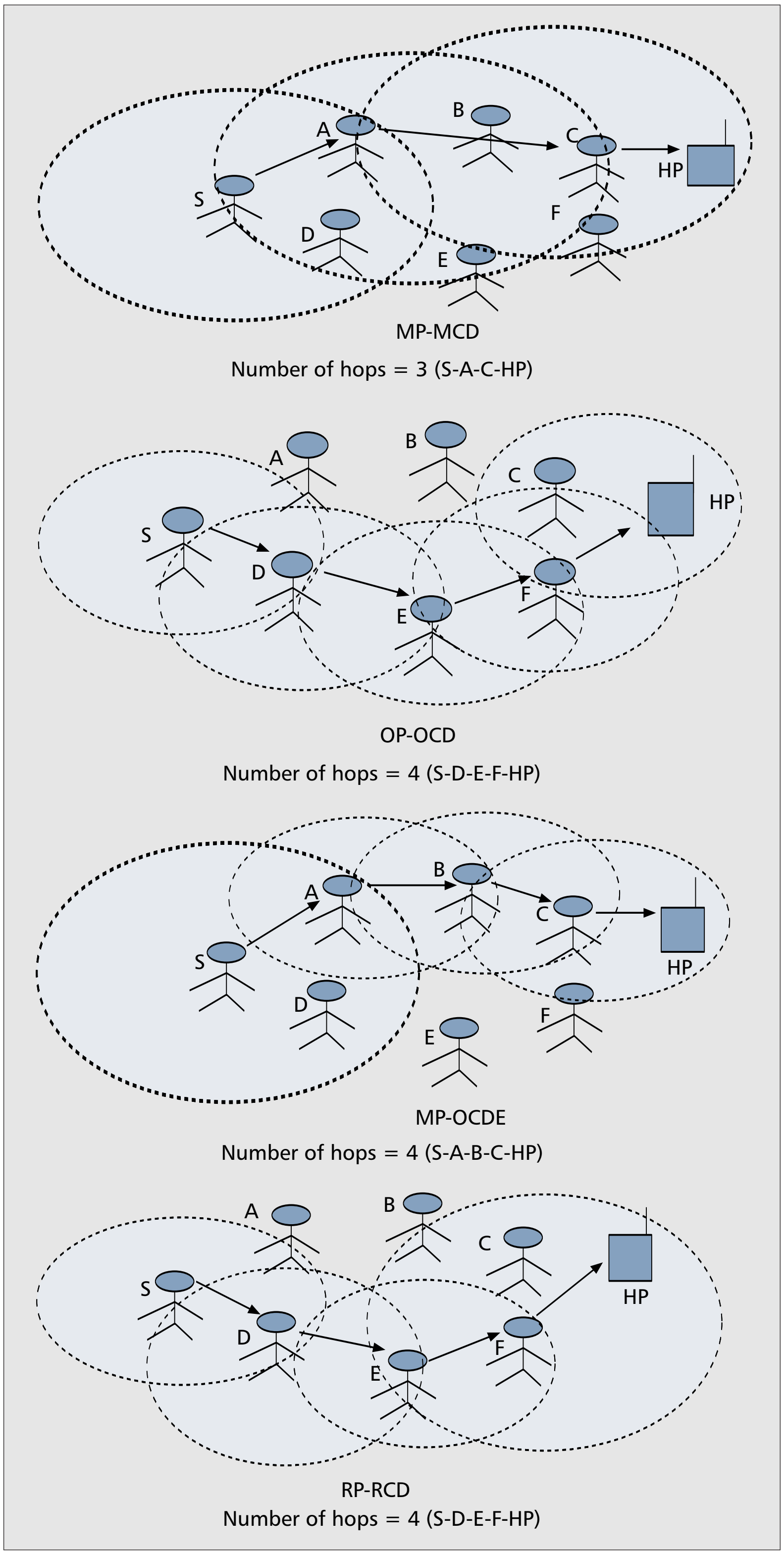
Optimal Power from Both Patient and Cooperating Devices (OP-OCD) — All devices attempt to transmit at an optimal (minimum) level of power to reach the nearest cooperating node, resulting in a higher level of power efficiency. Several different ways to compute the optimal power include the processing of prior transmissions/receptions to and from neighboring nodes using a table with several next-hop nodes and corresponding power. In simple terms, the optimal power could be a function of the power necessary to reach to the first *N* neighboring nodes, where *N* depends on the required reliability and the allowed level of processing. These computations will require additional processing power, thus offsetting the overall power conservation due to the optimal power transmission. In addition, OP-OCD could involve a longer route, an increased delay, and a lower reliability of message delivery than MP-MCD. In scenarios where the transmitting and routing devices are more scattered (low device density), OP-OCD may not work well, since the computation for optimal power to reach the next node could be equal to the maximum power level. The mobility of nodes can further affect the optimal power levels. OP-OCD may be suitable for nonemergency periodic transmission of routine vital signs, and for reducing the network traffic and achieving power conservation of devices in some cases.

Maximum from Patient and Optimum from Cooperating Devices (MP-OCD) — The patient's device transmits at the maximum power; however, the other devices transmit at the optimal power level to reach the nearest node. In addition to power conservation, this protocol could be considered the fairest protocol, as the patient's monitoring device transmits more power than other devices involved in routing. In some cases, the reliability performance of MP-OCD may even be better than OP-OCD, due to the fewer number of hops resulting from maximum power transmission from the source device. It is also applicable for situations involving nonemergency and periodic transmission of routine vital signs.

Random Power from Patient's Device and Cooperating Devices (RP-RCD) — RP-RCD is a simple protocol and requires no power information from other devices, and thus will save computational resources and time for monitoring devices. However, it could result in unpredictable levels of transmitted power and patient monitoring reliability. In some cases, the random level of power transmission can lead to significant power inefficiency, while in other cases, the message delivery may not be reliable due to too little power. The mobility of patients could add another layer of unpredictability for RP-RCD. In essence, we use it as the worst-case scenario for comparing the performance of other protocols.

The four protocols are compared in Table 1 and their operation with unicast routing is shown in Fig. 2. The number of hops and the route from a patient to a health care professional will depend on the power management protocol. For example, there are four hops in RP-RCD, three in MP-MCD, and four each in OP-OCD and MP-OCD. In general, the fewest hops are likely to be in MP-MCD due to maximum power transmission, while most hops will occur in OP-OCD due to optimal power transmission. In general, the number of hops in MP-OCD will likely to be somewhere in between these two. The power saving by OP-OCD, to some extent, may be offset by the power consumed in increased processing for deriving optimal power levels and a higher number of retransmissions for message delivery.

SLEEP STRATEGY AND ASSISTED POWER MANAGEMENT



MP-MCD
Number of hops = 3 (S-A-C-HP)

OP-OCD
Number of hops = 4 (S-D-E-F-HP)

MP-OCDE
Number of hops = 4 (S-A-B-C-HP)

RP-RCD
Number of hops = 4 (S-D-E-F-HP)

■ **Figure 2.** *Four protocols for power management.*

We propose that power conservation protocols can be combined with sleep strategy. Sleep strategy involves the saving of transmitted power at the physical layer; however, it could utilize the information from network and application layers to create a balance between reliability and power conservation. For patient monitoring, sleep strategy is specifically applicable in an area of high device density, allowing a few nodes to sleep while others could forward messages. To implement sleep strategy, devices with a high-level of available power budget, significant functionalities (such as battery power and processing), and the ability to route messages for others can be chosen as sleep coordinators. The devices under the sleep cycle can periodically wake-up to check any waiting messages or set of actions. The following factors from multiple layers (applications, network, and physical) could influence the sleep strategy: level of network connectivity, fairness

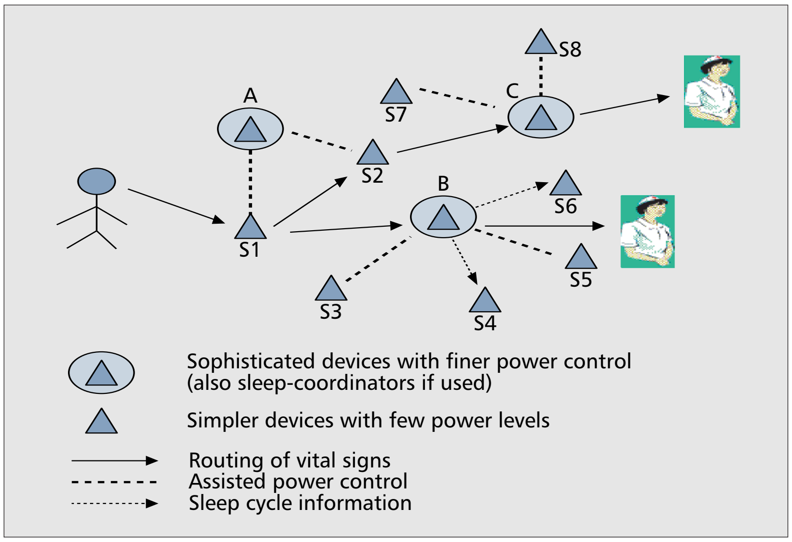


Figure 3. *Assisted power management and sleep strategy.*

of sleep times for devices, energy conservation, overhead of sleep strategy, and mobility levels of patients. For example:

- Devices of patients with little or no mobility can have longer sleep durations, especially if there are many other patients/devices in range.
- The 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).

To implement sleep strategy, there will be an increase in data traffic among several nodes requiring additional transmitted power. Our future work will involve estimating the increased power requirement for implementing sleep strategy and its offsetting effect on overall power savings due to sleep strategy. Based on the density of devices and the number of simultaneous devices in sleep, sleep strategy could negatively affect the reliability of message delivery for some emergency cases; therefore, additional work is necessary to devise an "optimal" sleep strategy to satisfy the reliability requirement of patient monitoring.

As shown in Fig. 3, a sleep coordinator such as a device A, B, or C with finer power control and higher processing capability can also be used for assisting other "simpler" devices in selecting one of the few possible power levels. This "assisted power control" can be combined with a sleep-control strategy and processed by the same set of more complex devices or by division/rotation of processing. Although the optimal power management may be complex, a more approximate power management can be attempted for devices with few power levels (low, medium, and high). As shown in Fig. 3, device A determines and informs devices S1 and S2 of their optimal 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.

The impact of assisted power management and sleep strategy on network reliability must be carefully assessed. Although these enhancements improve the power conservation of devices and thus improve the reliability of future transmissions at the device level (along with increasing the life of network), a poor implementation could lead to routing difficulties for emergency messages due to insufficient devices available for routing.

ALGORITHM FOR POWER-EFFICIENT AND RELIABLE PATIENT MONITORING

An algorithm for power-efficient and reliable patient monitoring is shown in Fig. 4. It is assumed that the patient is monitored continuously using monitoring devices that have been configured to meet the specific needs of the patient. The requirements of vital signs are derived by:

- Obtaining the vital signs in the analog domain from the patient monitoring device
- Digitizing the vital signs
- Obtaining the patient's specific health care information
- Deriving the level of emergency for the transmitted signal in terms of high, medium, and low, respectively indicating a life-threatening emergency, the presence of abnormal conditions, and in-range vital signs

This is done by comparing the current values of individual vital signs to the patient-specific thresholds by matching to a set of undesirable patterns of vital signs and by checking a combination of vital signs. For example, if two related vital signs are in abnormal range (too low or too high), then the level of emergency is much higher than if a single vital sign is in abnormal range. Based on the level of emergency and the number of devices in a certain area (device density), the patient monitoring device (PMD) or its proxy (in case a sleep strategy is selected) will select a power management protocol among MP-MCD, MP-OCD, and OP-OCD, as shown in Fig. 4a. We choose not to include RP-RCD due to its unpredictable level of transmitted power and reliability performance.

To reduce processing at the device levels, associated protocol details, such as the use of differential signals to reduce network traffic under normal vital signs and the use of multiple transmissions and Acknowledgment based scheme for higher reliability of message delivery, can be predetermined and configured in the patient monitoring devices. The number of retransmissions can be based on the time it takes to receive Acknowledgment from a health care professional and the duration between two successive transmissions, which can be adjusted based on the level of emergency of vital signs and network traffic.

The sleep strategy involves selecting one or more sleep coordinators, which will determine the number of devices in the sleep cycle under normal and emergency conditions. Factors such as the number of devices in a specific area and device mobility can be used in determining the use and length of sleep cycle and power levels for a device. The actions based on device density for sleep cycle and power management are shown in Fig. 4b.

The proposed ad hoc network-based patient monitoring satisfies several of the patient monitoring requirements, including:

- Reliability of patient monitoring
- Power conservation
- Support for both routine and emergency vital signs
- Support for both mobile and fixed patients
- Support for diverse patient-monitoring devices through implementation of assisted power control

Additional work is necessary for measuring the effectiveness of the proposed protocols, assisted power control, and sleep strategies with regard to:

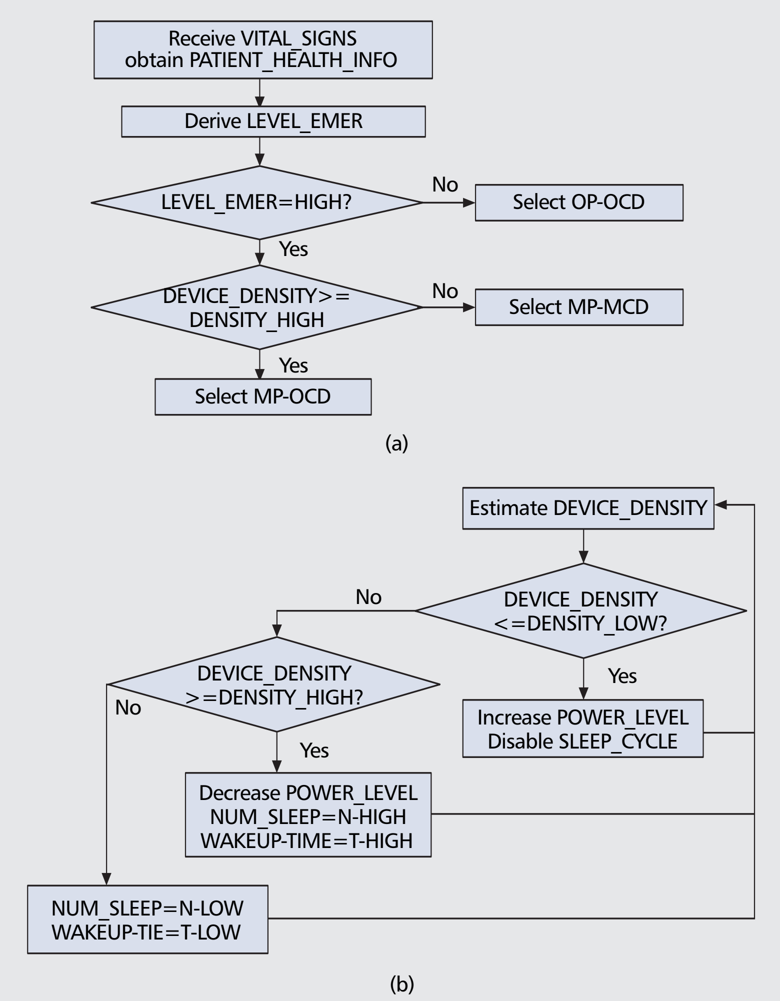
- End-to-end delay
- Scalability of the patient monitoring system
- Cognitive load on health care professionals

MODELING AND PERFORMANCE EVALUATION

In order to evaluate end-to-end reliability and protocols for power management, an analytical model has been developed. The model can estimate the end-to-end reliability and power needed for each of the protocol. The model is being extended to derive multimetric performance evaluation (reliability, power, and delay) for normal and emergency messages, assisted and self-power management, and several sleep strategies. Also, a suitable mobility model for characterizing the behavior of patients with slow and restricted mobility with long sojourn times at few locations in nursing homes and hospitals is being developed.

END-TO-END RELIABILITY

To measure the end-to-end reliability under varying user densities and numbers of hops, we varied the number of hops from two to ten by changing the distance covered by a single hop. The end-to-end distance was kept at a fixed value and the minimum number of hops was kept at two, as no device could cover the entire distance in one hop. For a given number of hops, all involved devices transmitted at the same power level, which was related to the square of the distance to the next hop. It was also assumed that the devices were uniformly distributed. The impact of user density and the number of hops on the end-to-end reliability of message delivery is shown in Fig. 5a. The end-to-end reliability increases with a decrease in the number of hops, and reaches 100 percent for five hops for a range of user density. As the number of hops is reduced, the power transmitted is increased in proportion to the square of the distance per hop. The resulting increase in covered area leads to a higher probability of finding one or more cooperating devices, which in turn improves the end-to-end reliability.



DEVICE_DENSITY: The number of devices in a given area
DENSITY_LOW and DENSITY_HIGH: Low and high thresholds used in deciding the use of sleep cycle for power conservation
NUM_SLEEP: The number of devices in sleep
N_HIGH and N_LOW: Two thresholds on the number of devices in sleep
WAKEUP-TIME: The duration of sleep before a device wakes up
T_LOW and T_HIGH: Two thresholds for sleep duration

■ **Figure 4.** *Algorithms for power-efficient and reliable patient monitoring: a) selection of power management protocol; b) power management and sleep cycle.*

COMPARATIVE PERFORMANCE OF PROTOCOLS

To obtain the maximum value of end-to-end reliability, the power transmitted by four protocols with varying user densities is shown in Fig. 5b. As expected, the highest power conservation is achieved by OP-OCD, followed by MP-OCD. The reduction in transmitted power is the result of an increased number of devices (or users) available in the coverage area. The average transmitted power for RP-RCD and MP-MCD are shown to be independent of user density due to the protocols' behavior of transmitting at a random level of power and a maximum level of power, respectively.

There are several interesting trade-offs that need to be measured in future work, such as the level of processing required in emergency cases, and trading-off complexity for achieving simple but somewhat inefficient patient monitoring, especially under emergency cases. The impact of assisted power management and sleep strategy

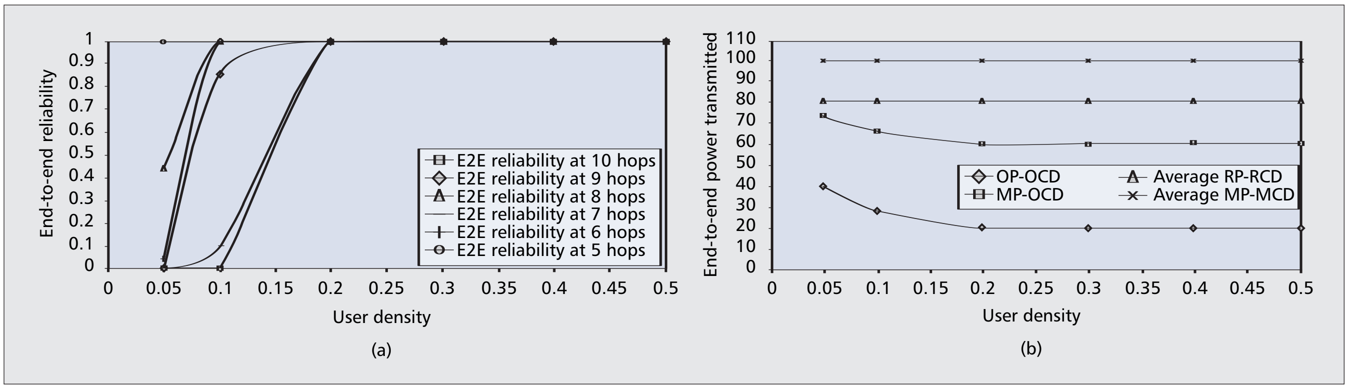


Figure 5. *a) The impact of user density on end-to-end reliability; b) the performance of four protocols under varying user density.*

on the end-to-end reliability of message delivery must also be measured.

CONCLUSIONS AND FUTURE RESEARCH

There are many challenges in wireless patient monitoring, including how to support reliable patient monitoring using ad hoc networks and how to manage power transmission from patients' devices. We have discussed support for reliable patient monitoring by designing protocols for power management for patients' devices, presenting assisted power management, and combining these with sleep strategy. Assisted power management can support a diversity of devices in order to provide a high reliability of message delivery at reasonable transmitted power. The performance results show that the proposed power management protocols can achieve high reliability under varying user densities, power levels, and numbers of hops. More specifically, OP-OCD achieves the best power utilization and MP-MCD leads to very high reliability (even under low device density). Future research may also include performance evaluation under diverse mobility patterns of patients in hospital, home care, and outdoor environments; design of hybrid wireless infrastructure; and development of a suite of protocols for reliable wireless patient monitoring.

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BIOGRAPHIES

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