Report Number: WUCSE-2008-25

2008-01-01

Reliable Data Collection from Mobile Users for Real-Time Clinical Monitoring

Octav Chipara, Christopher Brooks, Sangeeta Bhattacharya, and Chenyang Lu

Real-time patient monitoring is critical to early detection of clinical patient deterioration in general hospital wards. A key challenge in such applications is to reliably deliver sensor data from mobile patients. We present an empirical analysis on the reliability of data collection from wireless pulse oximeters attached to users. We observe that most packet loss occur from mobile users to their first-hop relays. Based on this insight we developed the Dynamic Relay Association Protocol (DRAP), a simple and effective mechanism for dynamically discovering the right relays for wireless sensors attached to mobile users. DRAP enables highly reliable data collection... **Read complete abstract on page 2.**

Reliable Data Collection from Mobile Users for Real-Time Clinical Monitoring

Octav Chipara, Christopher Brooks, Sangeeta Bhattacharya, and Chenyang Lu

Complete Abstract:

Real-time patient monitoring is critical to early detection of clinical patient deterioration in general hospital wards. A key challenge in such applications is to reliably deliver sensor data from mobile patients. We present an empirical analysis on the reliability of data collection from wireless pulse oximeters attached to users. We observe that most packet loss occur from mobile users to their first-hop relays. Based on this insight we developed the Dynamic Relay Association Protocol (DRAP), a simple and effective mechanism for dynamically discovering the right relays for wireless sensors attached to mobile users. DRAP enables highly reliable data collection from mobile users without requiring any change to complex routing protocols. We have implemented DRAP on the TinyOS platform and a prototype clinical monitoring system. Empirical evaluation showed DRAP delivered at least 96% of pulse oximetry data from multiple users, while maintaining a radio duty cycle below 2.8% and reducing the RAM footprint by 65% when compared to CTP. Our results demonstrates the feasibility and efficacy of wireless sensor network technology for real-time clinical monitoring.

Department of Computer Science & Engineering

2008-25

Reliable Data Collection from Mobile Users for Real-Time Clinical Monitoring

Authors: Octav Chipara, Christopher Brooks, Sangeeta Bhattacharya, Chenyang Lu, Roger Chamberlain,

Corresponding Author: ochipara@cse.wustl.edu

Abstract: Real-time patient monitoring is critical to early detection of clinical patient deterioration in general hospital wards. A key challenge in such applications is to reliably deliver sensor data from mobile patients. We present an empirical analysis on the reliability of data collection from wireless pulse oximeters attached to users. We observe that most packet loss occur from mobile users to their first-hop relays. Based on this insight we developed the Dynamic Relay Association Protocol (DRAP), a simple and effective mechanism for dynamically discovering the right relays for wireless sensors attached to mobile users. DRAP enables highly reliable data collection from mobile users without requiring any change to complex routing protocols. We have implemented DRAP on the TinyOS platform and a prototype clinical monitoring system. Empirical evaluation showed DRAP delivered at least 96% of pulse oximetry data from multiple users, while maintaining a radio duty cycle below 2.8% and reducing the RAM footprint by 65% when compared to CTP. Our results demonstrates the feasibility and efficacy of wireless sensor network technology for real-time clinical monitoring.

Type of Report: Other

Department of Computer Science & Engineering - Washington University in St. Louis
Campus Box 1045 - St. Louis, MO - 63130 - ph: (314) 935-6160

Reliable Data Collection from Mobile Users for Real-Time Clinical Monitoring

Octav Chipara[1], Christopher Brooks[1], Sangeeta Bhattacharya[1], Chenyang Lu[1], Roger Chamberlain[1], Gruia-Catalin Roman[1], Thomas C. Bailey[2]
[1]Department of Computer Science and Engineering, Washington University in St. Louis
[2]Washington University School of Medicine, Washington University in St. Louis

ABSTRACT

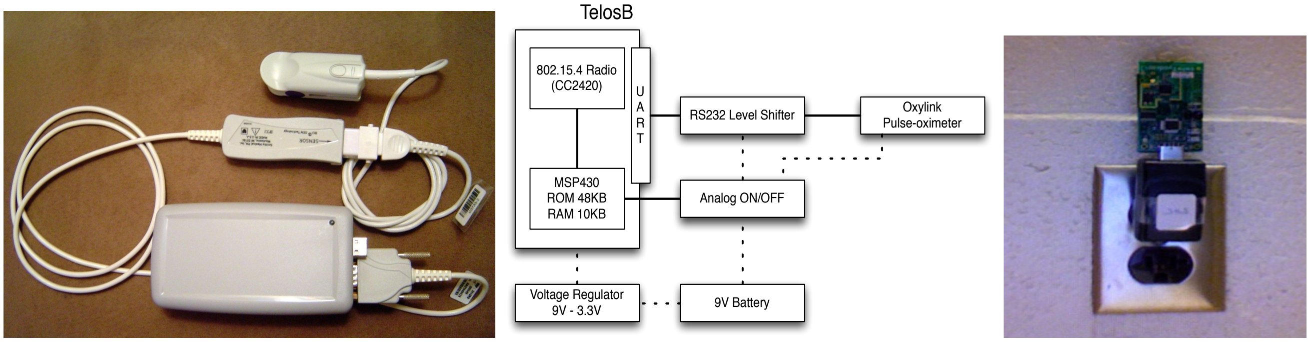
Real-time patient monitoring is critical to early detection of clinical patient deterioration in general hospital wards. A key challenge in such applications is to reliably deliver sensor data from mobile patients. We present an empirical analysis on the reliability of data collection from wireless pulse oximeters attached to users. We observe that most packet loss occur from mobile users to their first-hop relays. Based on this insight we developed the Dynamic Relay Association Protocol (DRAP), a simple and effective mechanism for dynamically discovering the right relays for wireless sensors attached to mobile users. DRAP enables highly reliable data collection from mobile users without requiring any change to complex routing protocols. We have implemented DRAP on the TinyOS platform and a prototype clinical monitoring system. Empirical evaluation showed DRAP delivered at least 96% of pulse oximetry data from multiple users, while maintaining a radio duty cycle below 2.8% and reducing the RAM footprint by 65% when compared to CTP. Our results demonstrates the feasibility and efficacy of wireless sensor network technology for real-time clinical monitoring.

1. INTRODUCTION

Early detection of clinical deterioration in patients is a key factor in reducing mortality rates and length of stay in hospitals. The prevalence of clinical deterioration resulting in cardiopulmonary or respiratory arrests for patients admitted to hospitals is between 4–17% [17]. In [9], an automated scoring system based on vital signs and other commonly recorded clinical data has been shown to identify patients at risk of clinical deterioration. Similarly, early detection and treatment of patients with sepsis, an infection induced syndrome resulting in systemic inflammatory response complicated by dysfunction of at least one organ, resulted in statistically significant lower mortality rates [8].

While the benefits of early detection are real, the sensitivity and accuracy of such systems hinges upon having timely clinical data [9]. This may not be a major problem for patients in Intensive Care Units (ICUs) since their vital signs are monitored by wired electronic monitoring systems. However, due to the significant cost of monitoring systems, the vital signs of patients in general wards are most often collected manually at long intervals. For example, even in postoperative care, nurses measure vital signs only 10 times in the first 24 hours following an operation [20]. This may lead to prolonged delays in the detection of clinical deterioration. Therefore, a real-time and reliable clinical monitoring system for patients in general wards is critical for effective early detection of clinical deterioration. The integration of real-time clinical data automatically collected from patients into electronic record systems has many important clinical applications. For example, an electronic scoring system can automatically generate alerts to a rapid response team in the event of patient deterioration, thereby reducing the delay of response from hours to minutes.

Emerging wireless sensor technologies hold the promise to meet the challenge of real-time clinical monitoring. Commercial medical device vendors are moving toward solutions that use 802.11 in their wireless patient monitoring systems. These systems require the deployment of wireless routers connected to a wired infrastructure. As a result, the monetary and deployment costs of such systems are high, making it feasible to operate them only in specialized departments such as cardiology. In contrast, our goal is to develop an inexpensive wireless clinical monitoring system for patients in general hospi-



(a) Custom-built wireless pulse-oximeter (b) Hardware components for wireless pulse-oximeter (c) USB power adapter

Figure 1: Hardware used for wireless clinical monitoring system

tal wards.

An attractive alternative to these commercial systems is to integrate off-the-shelf components. Several research groups have successfully prototyped devices that integrate low-power embedded platforms with various sensing modalities [11, 18, 4, 3, 2, 1, 10]. Our current prototype device integrates a TelosB mote (with a microcontroller and 802.15.4 radio), a standard pulse oximeter, and runs TinyOS, an open-source operating system. Furthermore, we may reduce the deployment time and cost of the system through mesh networking technologies, which require minimal infrastructure. In contrast to current systems in which a patient must be within the radio range of an access point connected to a wired local area network, we may route patient data to a base station over multiple wireless hops.

We identified two key challenges in developing a *reliable* wireless clinical monitoring system for general hospital wards. (1) In contrast to 802.11 radios, low-power radios are unreliable due to dynamic channel conditions [19] as well as susceptibility to interference [16]. (2) Unlike patients in ICUs, patients in the general hospital wards may be ambulatory. Patient mobility may lead to significant packet losses. Our work aims to address the challenge in reliable clinical monitoring for mobile users in general hospital wards. Specifically, the contributions of this paper are as follows: (1) Through systematic empirical studies on a prototype clinical monitoring system we find that the Collection Tree Protocol (CTP) [5] performed poorly under mobility. We identify the root cause of these problems to be the first hop; that is, the changing connectivity between the mobile node and the relay nodes. (2) We propose a simple yet robust data collection mechanism called ***D****ynamic* ***R****elay* ***A****ssociation* ***P****rotocol* (DRAP) which allows a sensor node to dynamically associate with a reliable relay node as the user moves in the environment. DRAP and existing data collection protocols which usually do not support mobile entities may be integrated for reliable data collection from mobile users. (3) Empirical results show that DRAP achieves at least 96% reliability and a radio duty-cycle of 2.2%. Moreover, DRAP reduces ROM and RAM usage by 27% and 65% when compared to CTP.

The remainder of the paper is organized as follows. Section 2 presents the related work. In Section 3, we present an overview of our initial system prototype which uses CTP. We evaluate the performance of this prototype through empirical studies which show poor performance in the presence of user mobility. These results are presented in section 4. In Section 5, we present the design of DRAP, which solves the problem of dynamic association between mobile and relay nodes. We evaluate the performance of DRAP through empirical studies performed on an indoor testbed. Concluding remarks appear in Section 6.

2. RELATED WORK

The mobile ad hoc network community has proposed numerous routing protocols with support for mobile entities [14,6]. It is common for routing protocols to introduce significant overhead by reconstructing a portion or an entire route in response to mobility-triggered routing failures. Due to reliability concerns and the characteristics of clinical environments, we deployed sufficient relay nodes to cover the area in which a user may move. As a result, a mobile node is always one hop away from a relay node. In the presence of relay nodes, the impact of mobility is limited to the first hop, i.e., the delivery of data from the mobile node to a relay. This enables us to avoid reconstructing end-to-end routes, making it possible to design a simple and efficient mechanism for reliable data collection from resource-constrained sensors attached to mobile users. DRAP features a mechanism that enables a mobile node to dynamically associate with relay nodes based on channel conditions or in response to mobility.

As part of the CodeBlue project [11], a publish/subscribe system that uses the TinyAMDR protocol [15] was proposed. TinyAMDR is an adaptation of the AMDR protocol [7] to wireless sensor networks. TinyAMDR handles mobility by restarting the route discovery process every 15 seconds. Thus, TinyAMDR suffers from the same issues as the routing protocols designed for mobile ad hoc networks.

A closely related work is an empirical study on the impact of the human body on the link layer properties of low-power radios [12]. The body impact on low-power links is characterized mainly through physical layer metrics such as: Link Quality Indicator (LQI) and Receive Signal Strength Indicator (RSSI). In contrast, our work focuses on the impact of user mobility on the routing layer and proposes a novel dynamic relay association protocol to achieve reliable data collection from mobile users. A novel MAC layer protocol that provides QoS for body networks is proposed in [21]. This protocol focuses on the communication between wireless sensors monitoring a single patient, whereas we emphasize the communication between a node placed on the body and relay nodes placed in the clinic.

A number of projects propose to use body sensor networks for different medical applications such as: assisted living [18,13], disaster response [4,3,2,1,10], and wireless clinical monitoring [11]. These systems emphasize architectural concerns, hardware and medical sensors choice, and specific application requirements. Unfortunately, those projects did not provide systematic study of their networking performance and reliability in the presence of mobile users, which is the focus of this paper.

3. SYSTEM DESCRIPTION

In this section, we first present the general system architecture. Next, we describe the wireless pulse oximeter sensor and a baseline software prototype that we developed for our study.

3.1 System Architecture

Our wireless clinical monitoring system consists of three types of nodes: a base station node, relay nodes, and patient nodes. The base station node is the endpoint of the data collection system and acts as a gateway between the wireless network and the electronic medical record system. The base station node is the only node that requires access to the wired network. Currently, the base station stores the received data in a PostgreSQL relational database. We plan to develop software for interfacing with electronic records for automatically updating patient vital signs and with automatic early detection systems.

The relay nodes are used to route packets from patient nodes to the base station when there is no direct wireless link between a patient node and the base station. Sufficient stationary relay nodes are deployed to cover the area in which users may move. Accordingly, a user is always one hop away from a relay node. Relay nodes may be connected to power outlets to reduce maintenance cost and enhance reliability. In our deployment, we experimented with using USB power adapters plugged into wall outlets (see Figure 1(c)) to power some of the nodes. In contrast to existing commercial telemetry systems, we do not require that the relay nodes have access to the wired network, thus removing the high wiring cost. Instead, the relay nodes form a multi-hop mesh network that covers the area of interest.

The patient nodes are carried by patients. A patient node integrates an embedded platform which provides computation, storage, radio, and sensors. The patient nodes are battery operated.

3.2 Wireless Pulse Oximeter

The relay and patient nodes use the TelosB mote as an embedded platform. TelosB has a 16-bit RISC processor with 48 KB code memory and 10 KB RAM. Wireless communication is provided using the CC2420 chip which is 802.15.4 compatible. The radio operates in the unlicensed 2.4GHz band and provides a raw bandwidth of 250 kbps. TelosB also features a 1MB external flash which may be used for data logging.

A patient node integrates the TelosB mote with the OxiLink pulse-oximeter from Smiths Medical OEM. OxiLink provides a standard RS232 interface operating at 10 mA with +6 to +13 VDC (see Figure 1(b)). Although the TelosB has a serial UART port needed to interface with the OxiLink device, it operates at TTL levels, whereas the OxiLink operates at RS232 voltage levels. This necessitated the design of a circuit to translate the voltage levels. To provide the different voltage levels required by the components (+3.3 VDC to the TelosB, +6 to +13 VDC to the OxiLink sensor), a single 9 V battery was used to power the embedded system. This provided power to the OxiLink sensor and a voltage regulator used to step the +9 V from the battery down to the required +3.3 VDC for the TelosB. To enable duty cycling we used an analog switch to turn power on and off to the sensor circuit. This switch is driven by one of the TelosB's configurable I/O pins. We developed a device driver for the pulse-oximeter in TinyOS 2.

Figure 2 shows the power profile of the pulse-oximeter we developed. The pulse-oximeter's device driver turns on the sensor only when a measurement is requested and turns it off after obtaining a valid measurement. It takes on average 6 seconds to obtain valid data from the OxiLink pulse-oximeter resulting in a 10% duty cycle when measurements are taken once a minute. When pulse and oxygenation data is collected every minute, the pulse-oximeter has an average lifetime of 83.6 hours when a 750 mA Lithium 9V battery is used. This lifetime is sufficient for our application since the average length of hospitalization is 3 days.

Mote	Sensor	Radio	Power Use
ON	-	-	6 mA
ON	ON	-	30 mA
ON	-	ON	25 mA
ON	ON	ON	49 mA

Figure 2: Power profile

3.3 Baseline Software Prototype

The goal of the initial software prototype was to reuse components provided by the TinyOS 2 operating system to develop a clinical monitoring system. This prototype allows us to evaluate state-of-the-art network protocols for real-time clinical monitoring, and provides a baseline for comparison against our new data collection approach presented in Section 5.

The most complex part of the system is the patient node. We deployed the following components on this node:

- The `OxylinkSensorC` component is the device driver for the pulse-oximeter. It implements the serial protocol necessary for communicating with the pulse-oximeter.
- The `PacketLoggingC` component allows for the logging of the packets received or transmitted by a node. The component may either relay the logged packets over the serial interface or store them in flash memory for later retrieval. This component proved invaluable for testing and debugging as well as for collecting the empirical data.
- The `CollectionC` component implements the Collection Tree Protocol (CTP) [5] which is the *de facto* data collection protocol for sensor networks. CTP is designed to be robust and efficient. CTP combines information from the routing, link and physical layers to evaluate link quality. It also employs an efficient protocol for route updates. CTP has been shown to provide close to 90% packet reliability for stationary networks [5]. However, in next section, we will show that CTP performs poorly in the presence of mobility. Later we will develop a new protocol that addresses this challenge.
- The `PatientAppC` implements the actual data collection application which collects pulse and oxygenation readings at a user-specified rate and routes them to the base station using CTP.

The same networking components used on the patient node are deployed on the relay nodes and the base station. In addition, on the base station we added a component which forwards over the serial interface any pulse and oxygenation data received wirelessly by the base station. In turn, a Python application reads this data and stores it in the PostgreSQL relational database for later retrieval.

4. EMPIRICAL STUDY

In this section, we present an empirical study of the reliability of our clinical monitoring system in an indoor environment. The experiment is designed to emulate a clinical environment with mobile patients. The testbed provides a realistic deployment scenario in which not all nodes have line-of-sight communication.

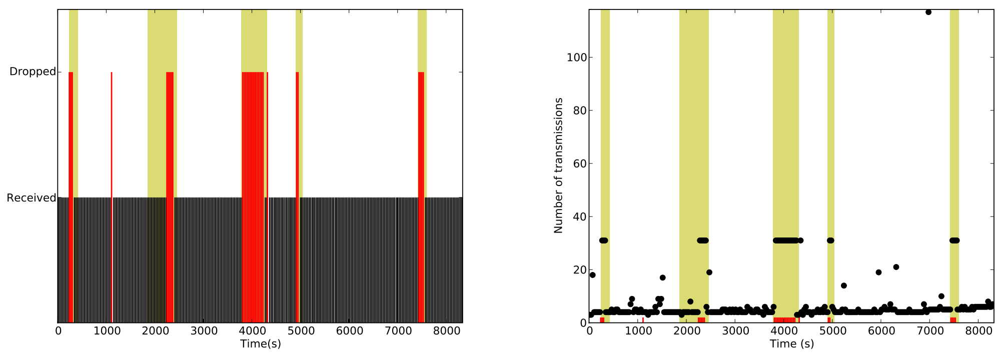
The experiments presented in this section were conducted on our wireless sensor networking testbed deployed in Jolley and Bryan Halls at Washington University in St. Louis (see Figure 3). The testbed consists of 30 TelosB motes located in Jolley Hall. All sensor data collected from sensor nodes are transmitted over the wireless mesh network. For instrumentation, each node is connected to a central server using a wired USB and Ethernet backbone. This backbone is used as a back-channel to issue commands to the motes and collect experimental results without interfering with ongoing wireless transmissions. In some experiments, an additional 7 TelosB motes were added to provide coverage in Bryan Hall. These nodes are not connected to the USB backbone and recorded their data in flash memory. The logged data was inserted in a database upon completion of each experiment. All experiments were performed using channel 24 which does not overlap with the 802.11 wireless network deployed in the same buildings.

We selected one of the motes to be the base station while the remaining nodes acted as relays. To better characterize the reliability of the system, we consider in this section the case when there is a single mobile user carrying a patient node in a pouch around his neck. Periodically, the patient node transmits pulse and oxygenation data along with other metadata indicating the quality of the measurements. The total payload size is 16 bytes.

To characterize the network reliability we introduce the following metrics. *End-to-end* reliability is the fraction of data packets received by the base station out of the total number of packets generated by the patient node. *First-hop* reliability is the reliability of the packet transmission over the first-hop, i.e., from the patient node to a relay node. First-hop reliability allows us to directly characterize the impact of user mobility on routing reliability. To fully characterize the impact on data collection we also use the *ETX* of a packet, i.e., the number of transmissions required to successfully deliver a sensor reading to the base station.

4.1 Impact of Mobility

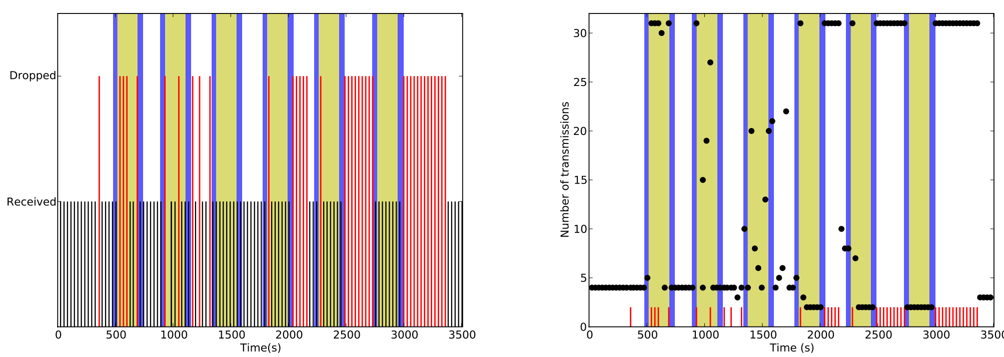
Figure 3: Testbed: Circles denote relay nodes which use USB and Ethernet backbone for logging and profiling. Diamonds indicate relay nodes deployed using USB power adapters plugged into wall outlets. A square denotes the base station. Positions A and B are used in the mobility study.



(a) End-to-end distribution of packet drops

(b) End-to-end distribution of ETX

Figure 4: CTP under normal activity. A white background color indicates that the volunteer was in his office; the yellow background indicates the volunteer outside his office.



(a) End-to-end distribution of packet drops

(b) End-to-end distribution of ETX

Figure 5: CTP under stress mobility. The background color in the graphs indicates the position of the subject at the time: white indicates the subject at position A, blue indicates the subject during the movement, and yellow indicates the subject at position B.

Normal Activity: To assess the feasibility of using wireless sensor networks for clinical monitoring we first performed a one hour experiment in which pulse and oxygenation were measured every minute. We chose this data rate because the pulse and oxygenation typically do not vary significantly within a minute. In addition, we performed a 2.5 hour experiment in which we increased the data rate to a reading every 30 seconds to better assess the impact of mobility. We asked the volunteers (graduate students and staff in the Department of Computer Science and Engineering) to (1) go about their normal routine and (2) record the times when they

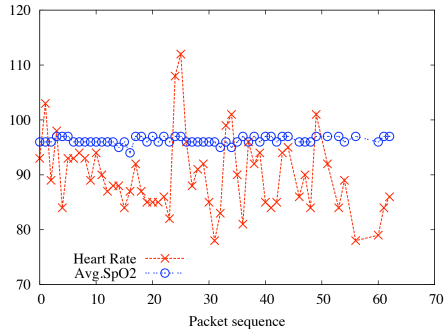


Figure 6: CTP under controlled mobility

leave their offices and when they return in order to correlate network reliability and mobility.

Figure 6 shows the vital signs collected during the one hour experiment from a single volunteer. The end-to-end reliability was 95.23% for the one hour experiment and 82.39% for the 2.5 hours experiment, respectively. Figure 4, shows the detailed results from the 2.5 hours experiment. A careful analysis indicates a strong correlation between user mobility and packet drops, as consecutive packet drops often occurred following periods of mobility. The first-hop reliability in the two experiments was 95.23% and 85.38%, respectively. This indicates that most of the packet drops occur during the first-hop transmission and that once a packet was delivered to the first relay, CTP was able to route the packets through the remaining hops with high reliability. We ruled out coverage gaps as a potential problem by verifying that all packets from the patient node were received by at least one relay node.

When asked to follow his normal activity, the subject left his office for 5% of the time in the first experiment and 20% of the time in the second experiment. Similarly variable mobility was observed in the multi-user study described in Section 5.2. To isolate the impact of mobility on CTP we ran a new set of experiments with more frequent user movement.

Mobility Stress Test: We hypothesized that the observed packet drops were due to poor routing table management. The patient node running CTP discovers nodes that are within its communication range. When the subject moves sufficiently to break the link to its current parent in the routing tree, CTP will attempt to transmit to the next best node in its routing table. However, since the subject has moved, many of the entries in the routing table may have been invalidated by the subject's movement and, as a result, CTP will attempt to transmit to nodes outside the patient node's communication range.

To test this hypothesis we asked a subject to move according to the following pattern: stay at position A for 3 minutes, move to position B, stay at position B for 3 minutes, and move back to position A (see Figure 3). This mobility pattern was repeated five times. Figure 5 shows the reliability of CTP under mobility. The pattern of packet drops indicates that our hypothesis is correct: packet drops tend to occur following changes in subject's location. The impact of mobility is even more pronounced when CTP's reliability is measured by ETX, which shows a sharp increase in the number of transmissions necessary to deliver the data successfully after each period of mobility. CTP uses Automatic Repeat reQuest (ARQ) to retransmit packets when they are not acknowledged. An ETX of 31 indicates a packet dropped in the first hop after exceeding the maximum number of transmissions.

CTP performed poorly under mobility, having an end-to-end reliability of 71.18% even when ARQ is enabled. The long sequences of packet drops are particularly disconcerting. The first-hop reliability was 72.88%, indicating that 97.67% of the packet drops occurred in the first hop. In contrast, if the packets from the mobile node are delivered reliably to the first relay node, then CTP's reliability is 97.67%. This suggests that the key research question is to develop a more reliable data collection mechanism from the mobile nodes to appropriate relays, which we call the *dynamic relay association problem* in this paper.

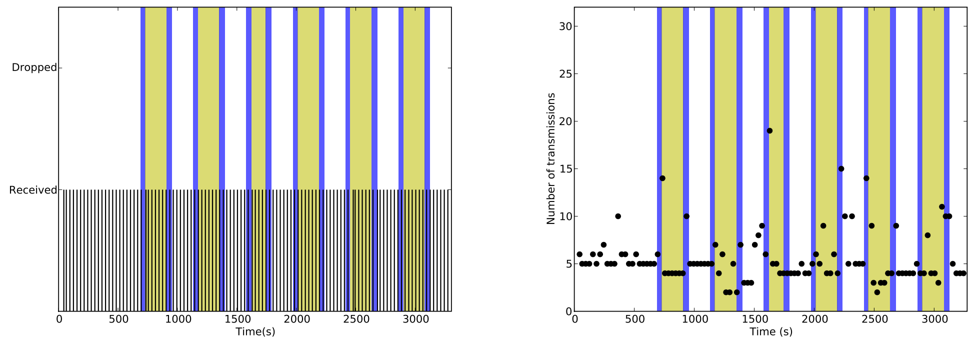
5. DYNAMIC RELAY ASSOCIATION

We developed the *Dynamic Relay Association Protocol* (DRAP) to achieve reliable data collection from mobile users to relay nodes. Based on the insights from the empirical study presented in Section 4, DRAP is not designed to be an end-to-end routing protocol for replacing CTP. Instead, it dynamically discovers and selects the right relay for the patient node to send its data while the user moves. DRAP complements routing protocols in that the former focuses on reliable data delivery over the first hop (from the patient node to the first relay), while the latter focuses on delivering data from the first relay to the base station. DRAP can therefore be easily integrated with existing data collection routing protocols such as CTP, as well as other wireless or wired relay networks.

The separation of DRAP from the routing protocol has several important advantages: (1) it enables reliable data collection from mobile users without any change to complex routing protocols; (2) it reduces the overhead (in terms of memory and bandwidth) on patient nodes, because DRAP does not includes many of the complex mechanisms required by end-to-end routing; and (3) it simplifies radio power management on the patient nodes as they do not participate in end-to-end routing.

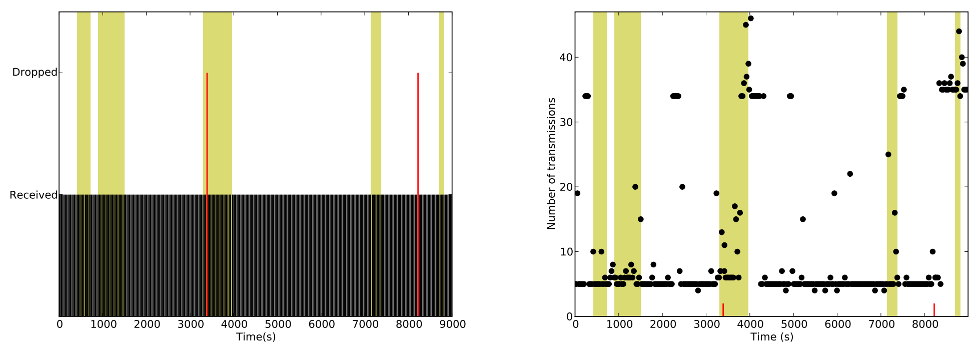
5.1 Design of DRAP

The key design challenge in DRAP is how to optimize



(a) End-to-end distribution of packet drops (b) End-to-end distribution of ETX

Figure 7: DRAP under stress mobility.



(a) Distribution of packet drops (b) Distribution of ETX

Figure 8: DRAP under normal activity.

for the common case when there is no mobility and to quickly react to user mobility. DRAP accomplishes this by associating a mobile node with the relay node that has the best link quality. DRAP detects when its relay table becomes outdated due to mobility by keeping track of the number of broken links. We consider a link to be broken when five packet transmissions remain unacknowledged.

DRAP uses feedback from both the physical and the link layers in making association decisions. The physical layer measures link quality in terms of RSSI. The RSSI link estimate is computed using a low-pass filter over the RSSI values from both beacons and overheard data packets. The link layer counts the number retransmissions of each packet before receiving an acknowledgement which henceforth we call the one-hop ETX (OETX). If OETX exceeds a set constant then DRAP removes that relay node from its relay table.

The way in which DRAP incorporates information from multiple layers is similar to that of the 4-bit link estimator used by CTP, however, DRAP makes use of this information to deal with mobility: the physical layer is useful when a link's quality degrades but OETX remains below a constant; in this case, the mobile node may change its association to a relay node that has a higher RSSI estimate. In contrast, the link layer provides information regarding broken links. If the number of detected broken links exceeds a constant, then DRAP assumes that its routing table is outdated due to mobility and removes all its entries.

DRAP's state diagram is shown in Figure 9. The protocol maintains three data structures: (1) a send queue containing all packets to be sent, (2) a relay table in which we maintain the address and an RSSI estimate for each link, and (3) the OETX of the packet at the head of the send queue. In DRAP, the relay nodes beacon periodically. A patient node starts in the *Radio OFF* state. Upon receiving a request to transmit a packet it turns the radio on and transitions to the *Radio ON* state. If the relay table is not empty, DRAP sends the packet to the relay node with the highest RSSI estimate. After sending the packet, it waits for an acknowledgement. If the acknowledgement is received, DRAP checks if there are any pending packet transmissions. If the send queue

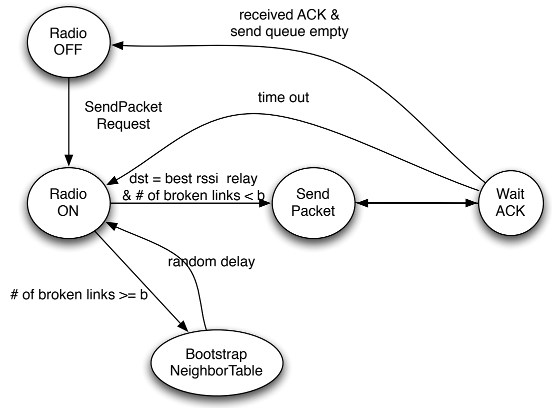


Figure 9: State diagram for DRAP

is empty, the radio is turned off and DRAP transitions to the *Radio OFF* state. If there are remaining transmissions, then the radio remains on.

If no acknowledgement is received, a timeout is triggered. When the OETX of the current packet is below a set constant, DRAP transitions to the *Radio ON* state and retransmits the packet to the relay with the best RSSI estimate. Otherwise, the entry associated with that relay is removed from the relay table. If the total number of broken links exceeds a threshold, DRAP flushes the entire table under the assumption that current routing information has been invalidated by mobility. The number of broken links is reset to zero upon successfully receiving an acknowledgement.

The threshold for the number broken links is a tradeoff between the expected churn caused by dynamic channel conditions and the possibility that a large number of entries are invalidated due to mobility: if the constant is set too low, DRAP will spend most of the time rebuilding routing tables without relaying packets or conserving energy; conversely, if the constant is set too high, DRAP will waste energy and bandwidth in transmitting numerous packets to nodes outside its communication range. In our experiments we set this threshold to two.

DRAP repopulates the relay table in the *Bootstrap* state. Upon receiving the first new beacon from a relay node DRAP waits a random delay before attempting to transmit the current packet. An additional delay is added to allow for the node to receive beacons from multiple relays and for handling the case when multiple patient nodes heard the same beacon. In the latter case, this may result in higher contention due to patient nodes sending packets simultaneously.

5.2 Empirical Evaluation

Overhead: DRAP is specifically optimized for body sensors with severe resource constraints. Figure 10(a) compares the memory footprint of the wireless clinical monitoring system when it uses CTP and DRAP. On the patient nodes, DRAP has a significantly smaller footprint: it reduces RAM and ROM usage by 65% and 27%, respectively. The reduction in footprint is attributed to the DRAP's simpler design than CTP. This result demonstrate that separating DRAP from routing is highly effective in reducing the footprint of patient nodes, which usually have more stringent memory constraint than relay nodes. On the relay nodes, using DRAP results in a slight increase in footprint since both CTP and the relay part of DRAP must run concurrently.

Figure 10(b) shows the number of packets received by the patient node when running CTP and DRAP under stress mobility. The results show a 74% reduction in the total number of packets transmitted or received. This result shows that DRAP introduces significantly lower communication overhead than CTP.

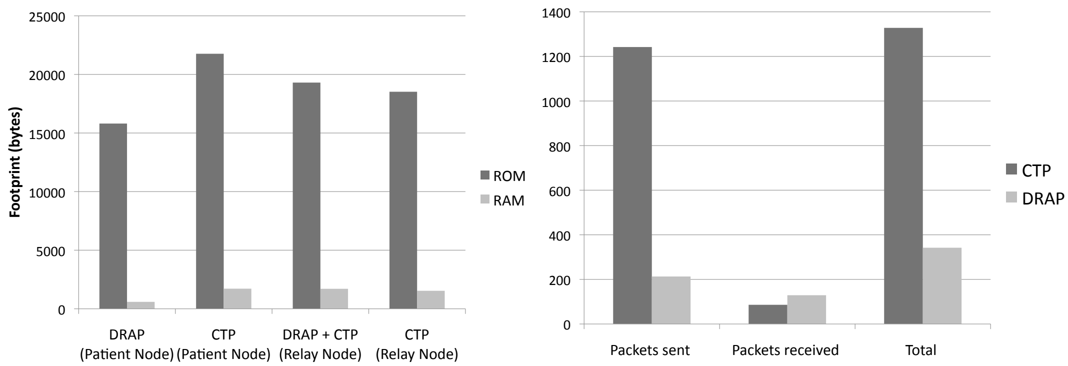
Single User Reliability Study: To evaluate the reliability of DRAP we reran the mobility experiments presented in Section 4. Figure 7 shows the reliability of DRAP under mobility stress. During the one hour experiment, we did not observe any packet drops as shown in Figure 7(a) and Figure 7(b). This is in sharp contrast to CTP which dropped 28.82% of the data in a similar experiment (see Figure 5).

Figure 8 shows the reliability of DRAP under normal activity. During the 2.5 hour experiment, DRAP dropped only 3 packets resulting in an end-to-end reliability of 99.33%. A duty cycle of 2.09% was observed in this experiment This indicates that DRAP achieved highly reliable data collection under both normal user activity.

Multiple User Reliability Study: To test the performance of our clinical monitoring system in the presence of multiple users, we monitored 7 healthy volunteers for an hour. The volunteers followed their normal activities while carrying our patient nodes. The end-to-end reliability of our system is shown in Figure 11. The end-to-end reliability for each user was in the range of 96-100%. We also measured the duty cycle of two of the volunteers which were 2% and 0.2%, respectively. The difference in the duty cycles may be explained by the difference in the mobility patterns of the two users. The user with more frequent movement had a higher duty cycle which is indicative of DRAP remaining awake to discover new neighbors.

Volunteer	End-to-end reliability
1	100.00%
2	98.33%
3	100.00%
4	100.00%
5	100.00%
6	96.15%
7	98.59%

Figure 11: End-to-end reliability for multiple users



(a) Memory footprint comparison (b) Communication overhead on patient node

Figure 10: Comparison of memory footprint and communication overhead

6. CONCLUSIONS

This paper proposes wireless patient monitoring as an enabling technology for early detection of clinical deterioration in general hospital wards. We present an empirical study on the reliability of real-time data collection from wireless pulse oximeters attached to users. We observe that the key challenge in such systems is to prevent packet loss from mobile users to their first-hop relays, while the standard data collection routing protocol called CTP can provide reliable data transport over stationary wireless relay networks. Based on this important insight we developed the Dynamic Relay Association Protocol (DRAP), a simple and effective mechanism for dynamically discovering right relays for wireless sensors attached to mobile users. The key advantage of DRAP is that it enables highly reliable data collection from mobile users without any change to complex routing protocols while introducing minimum resource overhead. We have implemented DRAP on the TinyOS platform and a prototype clinical monitoring system. Empirical evaluation showed DRAP delivered at least 96% of pulse oximetry data from multiple users, while maintaining a radio duty cycle below 2.8%. Furthermore, DRAP reduces the data memory footprint by 65% compared to CTP. Our results demonstrates the feasibility and efficacy of wireless sensor network technology for real-time clinical monitoring.

Acknowledgements:

The project described was supported in part by Award Number UL1RR024992 from the National Center For Research Resources. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Center for Research Resources or the National Institutes of Health. Further support was provided by NSF NeTS-NOSS Grant CNS-0627126 and CRI Grant CNS-0708460.

7. REFERENCES

[1] S. W. Brown, W. G. Griswold, B. Demchak, and L. A. Lenert. Middleware for reliable mobile medical workflow support in disaster settings. *AMIA Annual Symposium*, Jan 2006.

[2] D. W. Curtis, E. J. Pino, J. M. Bailey, E. I. Shih, J. Waterman, S. A. Vinterbo, T. O. Stair, J. V. Guttag, R. A. Greenes, and L. Ohno-Machado. Smart–an integrated wireless system for monitoring unattended patients. *Journal of the American Medical Informatics Association*, Jan 2008.

[3] T. Gao, D. Greenspan, M. Welsh, R. Juang, and A. Alm. Vital signs monitoring and patient tracking over a wireless network. *IEEE Engineering in Medicine and Biology Society Conference*, Jan 2005.

[4] T. Gao, T. Massey, L. Selavo, D. Crawford, B. rong Chen, K. Lorincz, V. Shnayder, L. Hauenstein, F. Dabiri, J. Jeng, A. Chanmugam, D. White, M. Sarrafzadeh, and M. Welsh. The advanced health and disaster aid network: A light-weight wireless medical system for triage. *IEEE Transactions on Biomedical Circuits and Systems*, Sep 2007.

[5] O. Gnawali, R. Fonseca, K. Jamieson, and P. Levis. Ctp: Robust and efficient collection through control and data plane integration. Technical Report SING-08-02, Stanford University.

[6] X. Hong, K. Xu, and M. Gerla. Scalable routing protocols for mobile ad hoc networks. *IEEE Network*, Jul/Aug 2002.

[7] J. G. Jetcheva and D. B. Johnson. Adaptive demand-driven multicast routing in multi-hop wireless ad hoc networks. In *MobiHoc*, 2001.

[8] A. E. Jones, M. D. Brown, S. Trzeciak, N. I. Shapiro, J. S. Garrett, A. C. Heffner, J. A. Kline, and Emergency Medicine Shock Research Network investigators. The effect of a quantitative resuscitation strategy on mortality in patients with sepsis: a meta-analysis. *Critical Care Medicine*, Oct 2008.

[9] A. Kho, D. Rotz, K. Alrahi, W. Cárdenas, K. Ramsey, D. Liebovitz, G. Noskin, and C. Watts. Utility of commonly captured data from an ehr to identify hospitalized patients at risk for clinical deterioration. *AMIA Symposium*, Jan 2007.

[10] J. P. Killeen, T. C. Chan, C. Buono, W. G. Griswold, and L. A. Lenert. A wireless first responder handheld device for rapid triage, patient assessment and documentation during mass casualty incidents. *AMIA Symposium*, Jan 2006.

[11] K. Lorincz, D. J. Malan, T. R. F. Fulford-Jones, A. Nawoj, A. Clavel, V. Shnayder, G. Mainland, and M. Welsh. Sensor networks for emergency response: Challenges and opportunities. *IEEE Pervasive Computing*, Oct 2004.

[12] E. Miluzzo, X. Zheng, K. Fodor, and A. T. Campbell. Radio characterization of 802.15.4 and its impact on the design of mobile sensor networks. In *EWSN*, January 2008.

[13] J. Modayil, T. Bai, and H. Kautz. Improving the recognition of interleaved activities. *UbiComp*, Sep 2008.

[14] R. Rajaraman. Topology control and routing in ad hoc networks: a survey. *SIGACT News*, 2002.

[15] B. rong Chen, K.-K. Muniswamy-Reddy, and M. Welsh. Ad-hoc multicast routing on resource-limited sensor nodes. *REALMAN*, May 2006.

[16] D. Son, B. Krishnamachari, and J. Heidemann. Experimental

study of concurrent transmission in wireless sensor networks. In *SenSys*, 2006.

[17] The Joint Commission. 2008 national patient safety goals. http://www.jointcommission.org/PatientSafety/NationalPatientSafetyGoals/08_hap_npsgs.htm.

[18] A. Wood, G. Virone, T. Doan, Q. Cao, L. Selavo, Y. Wu, L. Fang, Z. He, S. Lin, and J. Stankovic. Alarm-net: Wireless sensor networks for assisted-living and residential monitoring. Technical Report CS-2006-11, University of Virginia, Jan 2006.

[19] M. Z. Zamalloa and B. Krishnamachari. An analysis of unreliability and asymmetry in low-power wireless links. *ACM Transactions Sensor Networs*, 2007.

[20] K. Zeitz and H. McCutcheon. Policies that drive the nursing practice of postoperative observations. *International journal of nursing studies*, Nov 2002.

[21] G. Zhou, J. Lu, C. Wan, M. Yarvis, and J. Stankovic. Bodyqos: Adaptive and radio-agnostic qos for body sensor networks. *INFOCOM*, Jan 2008.