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Report Number: wucse-2009-82

2009

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Octav Chipara, Chenyang Lu, Thomas C. Bailey, and Gruia-Catalin Roman

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#### Recommended Citation

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Type of Report: Other

# Reliable Patient Monitoring: A Clinical Study in a Step-down Hospital Unit

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## ABSTRACT

This paper presents the design, deployment, and empirical study of a wireless clinical monitoring system that collects pulse and oxygen saturation readings from patients. The primary contribution of this paper is an in-depth clinical trial that assesses the feasibility of wireless sensor networks for patient monitoring in general (non-ICU) hospital units. The trial involved 32 patients monitored in a step-down cardiology unit at Barnes-Jewish Hospital, St. Louis. During a total of 31 days of monitoring, the network achieved high reliability (median 99.92%, range 95.21% – 100%). The overall reliability of the system was dominated by sensing reliability (median 80.55%, range 0.38% – 97.69%) of the pulse oximeters. Sensing failures usually occurred in short bursts, although long bursts were also present and were caused by the sensor disconnections. We show that the sensing reliability could be significantly improved through oversampling and by implementing a disconnection alarm system that incurs minimal intervention cost. Our results also indicate that the system provided sufficient resolution to support the detection of clinical deterioration in two patients who were transferred to the ICU. The results show the feasibility of using wireless sensor networks for patient monitoring and may guide future research. We also report lessons learned from the deployment in the clinical environments with patient users.

## 1. INTRODUCTION

Clinical deterioration in patients in general (non-ICU) hospital units is a major concern for hospitals. Of these patients, 4% – 17% suffer from adverse events such as cardiac or respiratory arrests [1, 6, 23]. A retrospective study found that as many as 70% of such events could have been prevented [16]. A key factor in improving patient outcomes is to detect clinical deterioration early so that clinicians may intervene before a patient's condition worsens. The detection of clinical deterioration is possible because most patients exhibit changes in their vital signs hours prior to an adverse event (median 6.5 hours, range 0 – 432 hours) [2]. Automatic scoring systems aimed at identifying clinical deterioration in patients based on their vital signs are being

developed [12, 13]. However, the performance of such systems is significantly affected by having up-to-date vital signs. This may not be a problem in Intensive Care Units where vital signs are monitored by wired monitoring equipment. However, the population that would most benefit from early detection of clinical deterioration is in general or step-down hospital units. In such units, vital signs are often measured manually at long time intervals. For example, in postoperative care, nurses measure the vital signs only 10 times during the first 24 hours following an operation [25]. This could lead to a prolonged delay until clinical deterioration is detected. Thus, it is necessary to develop a patient monitoring system for collecting the vital signs of patients on general hospital units.

Collecting vital signs in general hospital units poses unique challenges which are poorly addressed by existing commercial telemetry systems. First, for hospitals to deploy monitoring systems in general units they must be *inexpensive*. Existing medical telemetry systems use specialized 802.11 technology and require the deployment of numerous access points connected through a wired backbone. This system architecture results in high equipment and deployment costs making their deployment prohibitive outside specialized units. Second, in contrast to cardiac or epilepsy care which require high data rate EKG or acceleration measurements, the collection of vital signs<sup>1</sup> requires *low data rates*. This creates opportunities to reduce costs by matching hardware capabilities to application requirements: at low data rates, 802.11 may not be the optimal solution in terms of cost and energy consumption. Third, patients in general hospital units may be ambulatory. Hence, it is essential to develop a system which supports *patient mobility*. Moreover, it is unlikely that hospitals will be able to monitor all patients hospitalized in general units. Accordingly, it may be desirable to deploy wireless monitoring systems on a need basis, i.e., when a patient at high risk of clinical deterioration (e.g., who

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<sup>1</sup>The primary vital signs used for patient care in hospitals include temperature, blood pressure, pulse, and respiratory rate, which typically change over minutes.

just moved from the ICU to a step-down unit) is admitted to a general hospital unit, the system is *deployed on-demand*. This kind of on-demand deployment is not feasible in existing telemetry systems.

The requirements of low cost and low data rate motivate the development of a patient monitoring system using wireless sensor network (WSN) technology based on the IEEE 802.15.4 standard. While wireless sensor networks as gained attention as a promising technology for elderly care [24], disaster recovery [9], epilepsy care [20], and patient monitoring [7, 18], there has not a in-depth clinical study of the feasibility and reliability wireless clinical monitoring systems for in-patients in general hospital units. As a promising step towards real-time clinical detection systems for general hospital units, we present the deployment and empirical study of a wireless clinical monitoring system in a step-down cardiac care unit at Barnes-Jewish Hospital, St. Louis. The developed system monitors the heart rate (HR) and the blood oxygenation (SpO<sub>2</sub>). Data collected from 32 patients over a total of 31 days of monitoring shows that the median network and sensing reliabilities per patient were 99.92% and 80.55%, respectively. Somewhat surprisingly, the primary source of unreliability was sensing, not networking. While sensing failures occur frequently, the sensors recovered from most of the outages quickly. The distribution of sensing outages is long-tailed containing prolonged outages caused by sensor disconnections. Through trace analysis we show oversampling and automatic disconnection alarms that can substantially enhance sensing reliability with minimum manual intervention. Furthermore, our study indicates the feasibility to detect the clinical deterioration in the two patients who were transferred to the ICU during the trial.

The remainder of the paper is organized as follows. Section 2 presents the related work. The patient monitoring system is described in Section 3. The methods and results used during the clinical trial are presented in Section 4. Section 5 discusses our experience with the design and the operation of the patient monitoring system. Conclusions are presented in Section 6.

## 2. RELATED WORK

In this section we review existing medical systems and their empirical evaluation.

**Medical Systems:** Recently, a number of exciting medical systems have been developed in support of elderly care [24], disaster recovery [7, 9, 14], and patient monitoring [5, 7, 15, 19]. The monitoring of vital signs is a basic function which is supported by these systems. Due to the unique requirements of monitoring patients in general units, we made different design decisions. First, our system design takes advantage of the availability of power in hospital units. This is in con-

trast to disaster recovery and even in some elderly care settings. Second, some of the existing medical systems support peer-to-peer or publish/subscribe communication [3, 14]. In contrast, we opted for a simpler network architecture in which nodes forward the data to a single base station. Finally, we designed a novel solution for handling patient mobility.

**Empirical Evaluations:** Numerous patient monitoring systems using cell phones [5, 19], 802.11 [7, 9, 17], and 802.15.4 [4, 9, 18, 24] wireless technologies have been proposed. The evaluation of these systems typically does not focus on reliability and is usually performed in laboratories at a small scale. In the following, we summarize results obtained from patient monitoring systems deployed in clinical environments.

The MEDiSN [15] and SMART [7] projects focus on monitoring patients waiting in emergency rooms. In [15], networking statistics are collected in the emergency room at Johns Hopkins Hospital. The study focuses on understanding the low-level channel characteristics of a typical clinical environment which is particularly useful for developing novel wireless communication protocols. The study focuses on a small scale deployment and, more importantly, it ignores sensing reliability which we show to dominate the overall system reliability. In [7], pulse and oxygenation measurements were collected from 145 patients for an average of 47 minutes (range 5 minutes – 3 hours). No data regarding the reliability of the system is reported. Results from disaster drills are reported in [7, 9]; however, these results do not measure network performance or system reliability. In [4], we presented a preliminary description of our system. The system is evaluated using an indoor testbed and healthy volunteers. In sharp contrast, this paper provides a detailed description of the system and focuses on its evaluation in a clinical environment. The behavior of patients is known to differ significantly from that of healthy volunteers.

In contrast to prior empirical studies, the study presented in this paper involves real patients monitored by a large scale system over a long period of time. The patients were monitored in situ to realistically assess the feasibility of wireless sensor network (WSN) technology for patient monitoring. The system we deployed had 18 relay nodes and required multi-hop communication for data delivery. As part of the study, we monitored 32 patients recruited over six months for a total of 31 days of continuous monitoring.

## 3. SYSTEM

This section presents the system architecture, hardware components, and software we developed for the patient monitoring system. The presentation focuses on the key design decisions we made to meet the challenges of vital sign monitoring in general hospital units.

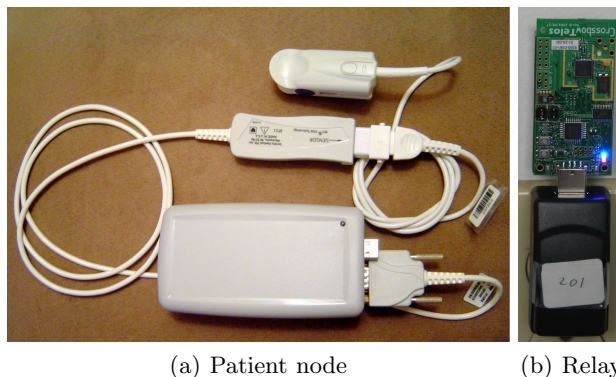


Figure 1: Hardware used for wireless clinical monitoring system

### 3.1 System Architecture

The patient monitoring system has a three tier architecture. The upper tier is formed by a *base station*. The base station runs a data collection application that saves the collected patient data in a local database. In addition, the base station supports remote login for debugging and data backup via an 802.11 link. The lower tier is composed of *patient nodes* (see Figure 1(a)). Patient nodes are worn by patients and are capable of measuring their heart rate and blood oxygenation. The middle tier is composed of *relay nodes* (see Figure 1(b)). The relay nodes self-organize in a mesh network that provides connectivity between the patient nodes and the base station. The delivery of patient data may involve multiple hops. Moreover, as patients may be ambulatory, we deploy sufficient relay nodes to ensure that a patient node is always one hop away from a relay node.

The system architecture has three features worth highlighting. First, unlike commercial systems, our system does not require the relay nodes to be connected to the hospital’s wired network. Table 1 shows the price of an 802.11 telemetry system sufficient for monitoring the patients in the step-down unit where the clinical trial was performed. It is worth noting that the access points used by the telemetry system have been modified to better support patient monitoring. The quote was obtained from through the hospital’s purchasing department. The equipment cost for our system is also shown. Even though a direct comparison between these figures cannot be made, the significant difference in infrastructure cost gives us confidence that the proposed system is significantly less expensive.

Second, in contrast to other environments in which sensor networks operate (e.g., environmental monitoring), power is widely available in hospitals. We take advantage of this by deploying the relay nodes using USB-to-power adaptors plugged into walls. This simple deployment approach, coupled with the self-organizing features of mesh networking protocols, are the basis for

System	Component	Units	Total price
802.11 telemetry system	Medical grade access points	5	\$20,498
	Ethernet switches	2	\$4,046
	Mounting kits	5	\$4,750
Our system	Sensor	20	\$8,000
	Infrastructure	18	\$1,800

Table 1: Prices for a typical 802.11 telemetry system and for the proposed system capable of monitoring the unit part of the trial.

supporting *on-demand deployment*. Note that power management policies are still necessary on patient nodes since they operate on batteries.

Finally, the proposed architecture isolates the impact of patient mobility: mobility may affect only the delivery of packets from the patient node to the first relay, while the remaining hops are over static relay nodes. As discussed in Section 3.3.1, this allows us to reuse the widely used Collection Tree Protocol (CTP) [10] for forwarding data over the static relays and develop a new protocol that finds the best relays to be used by a node even in the case of frequent mobility. Moreover, for similar reasons, we prohibit patient nodes to relay patient data. This has the additional advantage of simplifying the radio power management on sensor nodes.

### 3.2 Hardware

The relay and patient nodes use the TelosB mote as an embedded platform. Each TelosB mote has a 16-bit RISC processor with 48 KB code memory and 10 KB RAM. Wireless communication is provided using a 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 has a 1MB external flash which may be used for logging. We opted for the TelosB platform due to its low power consumption and low cost.

A patient node integrates a TelosB mote with a Ox-

iLink pulse-oximeter from Smiths Medical OEM. Both the OxiLink and TelosB support serial communication, albeit at different voltage levels. We developed a custom circuit board which performs the necessary voltage conversions to enable serial communication between them. The circuit also enables the TelosB to turn on and off the OxiLink through a hardware switch controlled by one of the TelosB’s I/O pins. This mechanism enabled us to duty-cycle the sensor as discussed in Section 3.3.2. Similar hardware capabilities have been developed and used as part of ALARM-NET [24], MEDiSN [15], AID-IN [9], SMART [7], and WIISARD [14] projects.

### 3.3 Software Components

The patient monitoring system was developed using the TinyOS operating system [11]. The system has three key software components: sensing, networking, and logging. Next, we describe each component.

#### 3.3.1 Network Components

TinyOS supports data collection from nodes through the *Collection Tree Protocol* (CTP). CTP is the *de facto* data collection protocol in sensor networks. CTP has been shown to achieve high reliability in static networks [10]. We developed an initial system prototype which uses CTP to collect data from patient nodes. In this prototype, CTP is deployed both on the patient and on the relay nodes. During the initial testing of the system, we observed that the end-to-end reliability was as low as 82% in the presence of mobility [4].

The following scenario may explain the root cause of the low reliability. The patient node discovers the nodes within its communication range and adds them to its neighbor table. Out of these neighbors, the patient node selects the neighbor with the lowest-cost path to the root as its parent. When the patient moves sufficiently to break the link to the current parent, CTP will select the next lowest-cost neighbor as parent. However, as result of mobility, it is likely that many of the neighbors in the neighbor table are now out of communication range. Accordingly, it is often the case that using the stale information present in the routing table would result in repeatedly selecting nodes outside the communication range of the patient node. Automatic reQuest Retry (ARQ) used by CTP exacerbates this problem by repeating a packet transmission multiple times (e.g., 31 times by default) before dropping the packet and changing the route.

In [4], we validated that CTP’s reliability problems were caused by mobility and, as a result, they were confined to first-hop: if a packet reached a relay node, then CTP delivered it to the base station with a relay reliability. Accordingly, a pragmatic approach to ensuring high end-to-end reliability is to isolate the impact of mobility by dividing the problem of data delivery from

patients nodes to the base station into two parts: from the patient node to the first relay and from that relay to the base station. We deploy CTP on the relay nodes to forward data to the base station since it achieves high relay over static relay nodes. Next, we designed a companion protocol called *Dynamic Relay Association Protocol* (DRAP) which is deployed on patient nodes to discover and select relays as the patient moves.

The design of DRAP must address three questions: how are neighbors discovered, how to select the best relay to associate with, and how to detect mobility. DRAP discovers new neighbors by listening for beacons periodically broadcast by the relay nodes. DRAP estimates the average Receive Signal Strength Indicator (RSSI) for each neighbor by using a low-pass filter over the RSSI values from both beacons and data packets. DRAP associates with the relay which has the highest RSSI estimate. As packets are sent to the current relay, DRAP keeps track of the number of packet failures. DRAP will invalidate the current neighbor when the number of retransmissions exceeds a threshold. DRAP’s approach of combining feedback from the physical (RSSI) and link layer (number of retransmission) in assessing link quality is similar to that proposed in [8]. The novelty of DRAP is that it can also detect mobility by using a single counter which keeps track of the number of *consecutive* relay invalidations: the counter is incremented when a relay is invalidated and reset to zero when data is successfully delivered to a relay. When the counter exceeds a threshold, DRAP flushes the neighbor table and rediscovers neighbors using its discovery mechanism.

DRAP features a lightweight mechanism for detecting mobility well-suited for the resource constrained devices we are using. We showed that the combination of DRAP and CTP, achieved high reliability even in the presence of mobility. However, the previous results were obtained on a sensor network testbed at Washington University in St. Louis. The results reported the performance of DRAP and CTP over short period of time. In contrast, the results presented in this paper are obtained from monitoring patients in a step-down hospital unit. A total of 31 days of networking statistics have been gathered during the trial.

The radio may have a significant contribution to the energy budget of patient nodes. In low data rate applications, the radio wastes most of the energy when it is active without transmitting or receiving packets. To address this issue DRAP is augmented with the following power management policy. Typically, power management protocols involve mechanisms that enable a sender and a receiver to coordinate the exchange of packets. These mechanisms assume that power management is performed on both the sender and the receiver. However, in our system, the relay nodes do not require

power management since they are plugged into wall outlets. Accordingly, the patient node could turn on the radio when it has a packet to transmit and turn it off after the associated relay acknowledges the reception of the packet. This simple policy handles the bulk of the traffic sent from the patient node to its associated relay without requiring any coordination between them. However, a problem arises during the discovery phase of DRAP: the patient node must be awake to receive beacons from the relay nodes. This problem is solved by keeping the radio awake when the neighbor table is empty (e.g., after it was flushed due to mobility or when a node boots up) for a fixed period of time after the discovery of the first relay node. This allows DRAP to populate its neighbor table with several relays.

This policy has two salient features. First, in contrast to existing power management schemes, DRAP requires neither time synchronization nor additional packet transmissions. Second, the policy is flexible in that the time the radio of a patient node remains active changes based on the observed link dynamics, variations in workload, and mobility. During the clinical trial we measured the duty cycle of the radio component on several patient nodes. The radio component had a duty cycle between 0.12% – 2.09%. The difference in duty cycles is the result of the DRAP protocol actively changing the associated relays. This is the cumulative result of variations in link quality over time as well as patient mobility.

### 3.3.2 Sensor Component

The sensor component supports serial communication between the TelosB mote and the OxiLink pulse-oximeter and performs power management. The sensor component measures pulse and oxygenation at user specified rates. Accordingly, every sensing period, the OxiLink sensor is turned on by signaling a hardware switch on the custom board to power up the sensor. The OxiLink sensor provides an indication of the validity of each measurement. The values reported by OxiLink are averages over 8 seconds. As a result, during the first eight seconds after the sensor is powered up, it reports invalid measurements; subsequent measurements may be valid or invalid. Patient movement or improper sensor placement may lead to invalid measurements. The sensor component reads the measurements provided by the OxiLink sensor continuously until a valid reading is received for up to 15 seconds.

### 3.3.3 Logging Component

We have developed a logging component which is primarily used for debugging and profiling the patient monitoring system. The logging component dedicates a significant portion of the RAM to buffer the generated statistics. Periodically or when the buffer is about to be full, the content of the RAM is saved to the flash in a



**Figure 2: Deployment at Barnes-Jewish Hospitals. The blue square denotes the base station. Red circles denote relay nodes.**

single batch. We found that batching the flash writing can significantly reduce the amount of time the flash is active, hence reducing energy consumption.

## 4. CLINICAL STUDY

To evaluate the feasibility of WSN technology for patient monitoring in step-down or general hospital units, we performed a clinical trial. The trial focuses on answering the following questions:

1. How reliable is the patient monitoring system?
2. What is the distribution of failures for the sensing and networking components?
3. How often nurses need to intervene to achieve high reliability?
4. Does the system provide sufficient resolution for detecting clinical deterioration?

In the subsequent sections, we will answer these questions.

### 4.1 Methods

We deployed the patient monitoring system in a step-down hospital unit at Barnes-Jewish Hospital. We opted to perform the clinical trial in a step-down unit rather than a general unit because patients in step-down units have higher risk of clinical deterioration. Accordingly, there is a higher likelihood that clinical deterioration will be observed during the trial. The step-down unit provides cardiac care for 32 patients and is already equipped with a patient monitoring system.



This study was approved by the IRB of Washington University in St. Louis. Participants were recruited in two phases: the unit’s head nurse identified patients which were responsive; we then sought the consent of the identified patients to participate in the trial. On average, one in six patients accepted participation in the trial. The main reason for denying participation was the inconvenience of wearing two monitoring devices: one provided by us and the one already used in the unit. We expect the acceptance rate to be higher on units without telemetry systems.

After obtaining consent, a patient node was placed in a telemetry pouch around the patient’s neck. Patients were monitored continuously until their discharge or for up to three days. During this time, patients often left the unit for treatment. The nursing staff recorded the times when a patient was not monitored by our system using a time sheet posted in the patient’s room. A total of 18 such events were recorded for the 32 participants. This suggests that these events were underreported. The data collected while the patient was not in the unit is excluded from presented results. Upon discharge, the statistics stored in the flash of the patient node was downloaded and stored in the database. This data indicated whether the sensor reported a valid measurement, whether the data was successfully delivered to a relay node, and the duty cycle of the radio, flash, and sensor components. New 9V batteries, monitoring pouches, and disposable pulse-oximetry sensors were used for each patient. After each use, the patient node was disinfected with a concentrated bleach solution.

The data collected by the monitoring system was not available to the nursing staff. The hospital was not obliged to act based on the measurements collected by our system. We verified that the measurements taken from patients were valid infrequently (usually daily). If the data provided were invalid, the nursing staff was notified to check if the sensor was disconnected.

The unit has 14 patient rooms and covers an area of 1200 m<sup>2</sup>. We deployed 18 relay nodes to provide coverage within the unit as shown in Figure 4. Most of the relays were placed in the patient rooms. Hospitals have two independent power circuits: one dedicated for critical equipment and one for non-critical equipment. The relay nodes were plugged into the power outlets on the power circuit dedicated to non-critical equipment. During the trial, the custodial staff unplugged the relay nodes on occasion to power their cleaning equipment. In addition, two relays were destroyed by impact with mobile equipment.. Due to the redundancy of the deployed relays, neither of these events had adverse effects on network reliability. The base station was deployed in a room behind the nurse’s station. The base station was powered and access to the hospital’s 802.11 wireless network was provided. The system operated on 802.15.4’s

Variable	Number
Gender	19 male 13 female
Age	average 65 range 34 – 89
Race	17 Caucasian 14 African American 1 undeclared
Adverse events	2 patients transferred to ICU
Total	32
Monitoring time	30 days, 23 hours, 42 minutes

**Table 2: Study statistics**

channel 26 such that it would not interfere with the existing 802.11 network or other telemetry systems. Over the time of deployment, the maximum number of hops varied between 3 – 4.

Patients were enrolled in the study between June 4 and December 4. During this time, a total of 32 patients were enrolled. Demographic data is presented in Table 2. We excluded the results of three patients from the presented statistics. The data from the first patient admitted to the trial was excluded because it had significantly lower network reliability. We determined that an older version of CTP was the source of the problem and updating it to the latest version available solved this issue. The other two patients were excluded because we collected no data from them. This was the result of a improperly handled exception in the data collection code running on the base station.

The pulse and oxygenation were measured at 30- and 60-second intervals. We selected sampling two rates to gain insight on the impact of sensing rate on sensing reliability and energy consumption. Note that at these rates the resolution provided by our system is orders of magnitude higher than that achieved by manually collecting vital signs. The system collected about 31 days of pulse and oxygenation data. On average, each patient was monitored for 25.63 hours with a range of 2 – 69 hours. The system most commonly monitored a single patient with up to three patients at a time. During the trial the condition of two patients deteriorated and they were moved to the ICU.

## 4.2 Reliability

In this section, we provide a detailed analysis of the system reliability. To quantify the reliability of the patient monitoring we introduce the following metrics:

- *Network reliability* is the fraction of packets delivered to the base station.
- *Sensing reliability* is the fraction of valid pulse and oxygenation readings received at the base station. The pulse oximeter provides an indication of the validity of each reading.

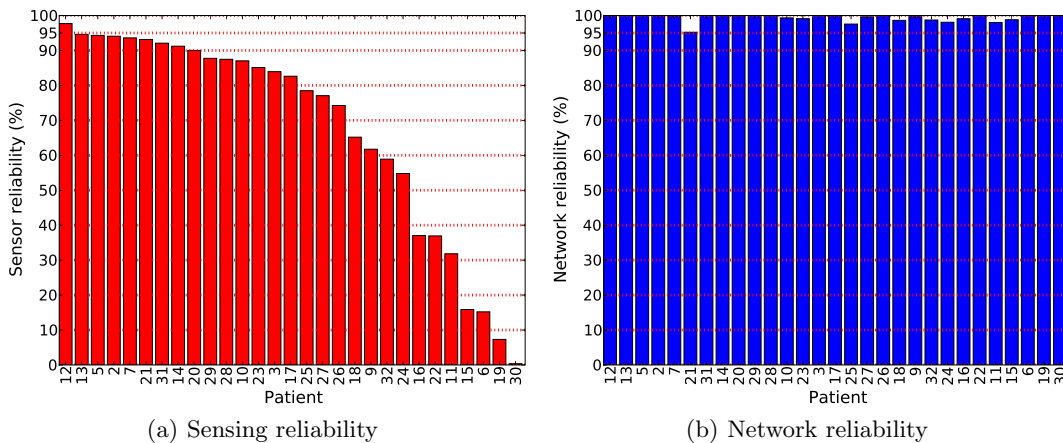


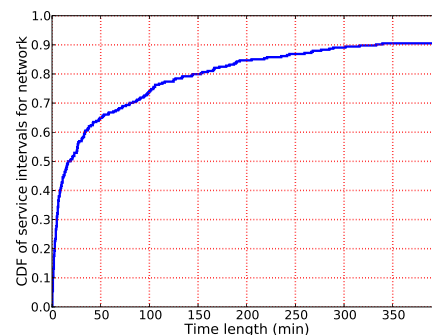
Figure 3: Network and sensing reliability per patient

To better understand the distribution of failures for the sensing and networking components, it is useful to define *service intervals* and *service outages*. A service interval is a continuous time interval that a component operated without a failure. A network failure refers to the case when a packet is not delivered to the base station, while a sensing failure refers to pulse-oximeter obtaining an invalid measurement. The pulse-oximeter provides an indication of the validity of each reading. A service outage is the time interval from when a failure occurs until a component recovers. The length of *service intervals* is a measure of how frequent failures occur while the length of the *service outages* is a measure of how quickly a component recovers after a failure.

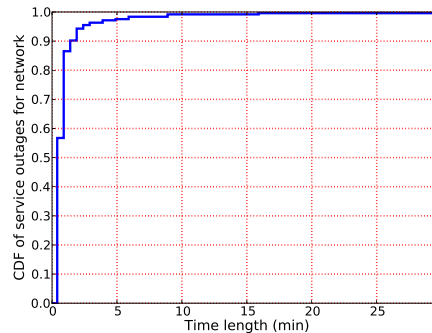
#### 4.2.1 System Reliability

Figure 3 plots the network and sensing reliability of each patient. As shown in Figure 3(b), the system achieved a median network reliability of 99.92% (range 95.21% – 100%). In contrast, the sensing reliability was significantly lower (see Figure 3(a)). The median sensing reliability was 80.55% (range 0.38% – 97.69%).

Several key observations may be drawn from this data. First, the results indicate the system achieved high network reliability for *all* patients in spite of dynamic channel conditions and relay failures. This demonstrates the robustness of CTP and DRAP. Second, the median sensing reliability is sufficient to provide health practitioners with pulse and oxygenation data at two orders of magnitude higher resolution than that achieved through manual collection. However, the wide range of the sensing reliability is disconcerting: seven patients had reliability below 50%. An in-depth analysis of sensing reliability is deferred to Section 4.2.3. Third, the overall system reliability is dominated by sensing reliability rather than networking reliability. This shows that our future efforts should focus on devising mechanism for improving sensing reliability. Further improvements in



(a) CDF of service intervals for network



(b) CDF of service outages for network

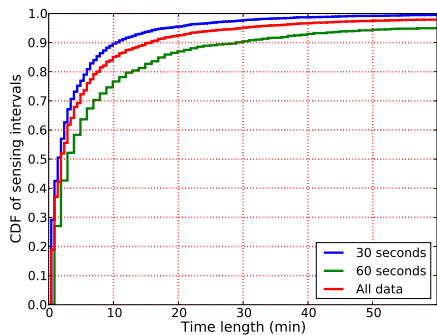
Figure 4: Distribution of service intervals and outages for network component

networking performance would result in minor improvements in system reliability.

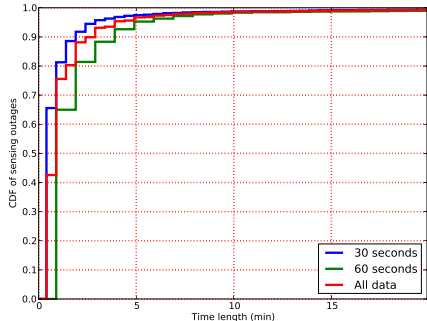
**Result:** *The overall system reliability is dominated by sensing reliability.*

#### 4.2.2 Network Reliability

To analyze the network reliability in greater detail, we consider the distribution of the length of service intervals and outages. Figure 4(a) plots the CDF of the



(a) CDF of service intervals for sensor



(b) CDF of service outages for sensor

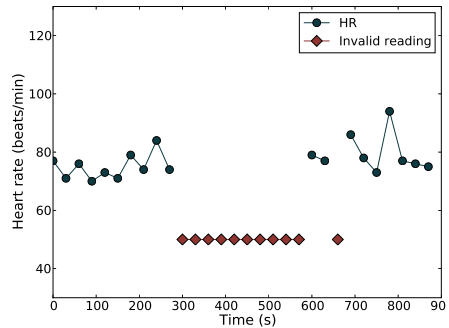
**Figure 5: Distribution of service intervals and outages for the sensor component**

service intervals for all patients. The graph shows that the median service interval is 17.7 minutes. Figure 4(b) plots the CDF of the service outages for all patients. The graph shows that 80% and 90% of the services outages are less than 0.86 and 1.41 minutes, respectively. Since the measurements are taken every 30 or 60 seconds, we may conclude that it is unlikely to observe more than 2 – 4 consecutive packet drops. Thus, the network components recover from failures quickly.

**Result:** *The network component provides high reliability: networking failures are infrequent and recovery often occurs within a minute.*

We profiled the behavior of DRAP for twelve of the patients. DRAP remained associated with the same relay for five of the patients. This is justified by the low noise level on 802.15.4’s channel 26 which does not overlap with other wireless devices. For the remaining seven patient nodes, DRAP changed the relay association at least once. DRAP indicated that mobility was responsible for changes in relay association in four cases. The frequency of mobility was significantly lower than that we previously observed with healthy volunteers [4]. It is also worth mentioning that during the trial a two patients switched rooms. No manual system configuration was necessary for handling this change.

### 4.2.3 Sensing Reliability



**Figure 6: Impact of movement on sensing**

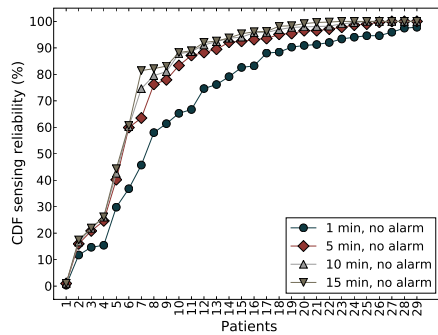
The quality of pulse and oxygenation readings was significantly affected by patient movement, sensor disconnections, sensor placement, and nail polish; this experience is consistent with results previously reported in literature [21]. Patient movement which includes movement of the arm on which the pulse oximeter was placed, finger tapping, or fidgeting may lead to invalid readings. The impact of patient movement may be significant (see Figure 6): when a volunteer moved his hand up and down (300 – 600 seconds), none of the obtained measurements were valid. In contrast, when the patient did not move his arm, a single measurements was invalid. Sensor disconnection also had a significant impact: in 11 of the 32 patients there were sensor disconnections longer than 30 minutes.

The distribution of service intervals and outages for the sensor component is shown in Figure 5. We remind the reader that a sensing failure occurs when the pulse oximeter sensor reports an invalid reading. The median service interval is 2.00 minutes, as shown in Figure 5(a) when the data from all patients is considered. As few as 8.6% of the service intervals are longer than 17.7 minutes (the mean service interval for the network component). The short duration of service intervals indicates that sensor failures are common.

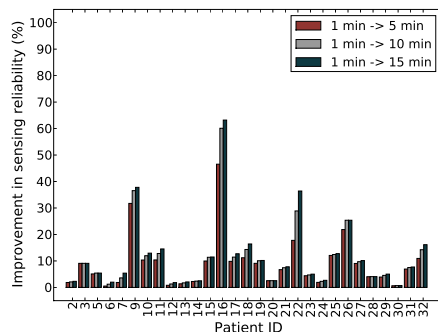
Figure 5(b) plots the CDF of the duration of service outages. The figure provides two important insights. First, most of the sensing outages are short: 75.2% of the outages last for less than a minute. This suggests that the sensing distribution is characterized by frequent failures which occur in short bursts. These types of failures are the result of patient movement or improper sensor placement. Second, the distribution of service outages is long-tailed: 0.69% of the sensing outages are significantly longer than 20 minutes. The longest service outage lasted 14.3 hours. These long outages are due to sensor disconnections. Nurses did not have access to the patient’s data and checked for disconnections infrequently. In section 4.3, we consider the effectiveness of an alarm system both in terms of its alarm rates and in on the number of interventions

required by the nursing staff.

**Result:** *The sensor failure distribution is characterized by frequent failures which usually occur in short bursts; disconnections cause prolonged sensing failures.*



(a) Impact of oversampling



(b) Improvement in reliability

**Figure 7: Impact of oversampling on sensing reliability**

Since sensing most failures occur in short bursts, the sensing reliability may be improved through oversampling: the sensor could take measurements at rate higher than the one specified by the doctor. Figures 5(a) and 5(b) also plot the service intervals and outages when measurements were taken every 30 and 60 seconds. Data indicates that increasing the sampling rate from one sample per minute to two, results in shorter service intervals as well as shorter service outages. The reduction in service outages is expected because the sensor is sampled at a higher rate. The 90-percentile of the service outages is reduced from 3.9 minutes to 1 minute when the sampling rate is increased from once to twice a minute. The short service outages also explains the increase in the prevalence of short service intervals: since numerous outages are shorter than 30 seconds, then when sensor is sampled at a higher rate, some of the outages may not be observed. The median sensing reliability of the patients monitored at 30 and 60 seconds were 84% and 79%, respectively. This shows that oversampling leads to improved reliability.

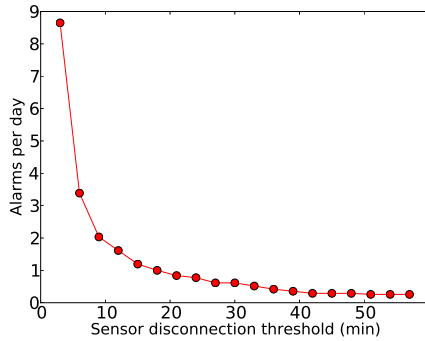
**Result:** *The sensing reliability may be improved through*

*oversampling.*

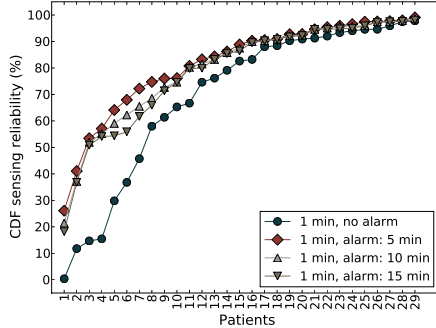
To further quantify the impact of sampling rate on sensing reliability, we consider the reliability of the system when the requirement of receiving valid pulse and oxygenation is relaxed to receiving at least one valid reading every 1, 5, 10, and 15 minutes. The updated sensing reliability results are computed based on the collected traces sampled at 30 and 60 seconds. As expected, the sensing reliability per patient increases as the sensing requirement is relaxed, as shown in Figure 7(a). In fact, as can be seen in Figure 7(b), the increase in sensing reliability can be as much as 62.4%. The patients which benefited most from these improvements had medium and low reliability sensing reliability. Most of the performance improvements were observed when the sensing requirement was increased to 5 minutes; further reductions in the sensing requirement resulted in smaller improvements. This may be explained by the fact that the bursts of sensing errors are short. The highest additional increase in reliability from lowering the sensing requirement from 5 minutes to 10 minutes was 13.4% for patient 16; while the highest additional increase in reliability for lowering the sensing requirement from 10 minutes to 15 minutes was 7% for patient 22. While the sensing reliability of most patients improved, it is worth mentioning that oversampling had no impact on the sensing reliability of eight patients. In the case of these patients, the low reliability was caused by the sensors becoming disconnected rather than intermittent failures. Hence, reducing the sampling requirement had no impact.

### 4.3 Benefits of Disconnection Alarms

As previously discussed, when a sensor became disconnected, the nursing staff should be notified to adjust the sensor. We propose an alarm system to notify the nursing staff when the sensor is disconnected. A disconnection may be detected by keeping track of the time since the last valid sensor reading was obtained by the sensor. When this time exceeds a disconnection threshold, the alarm is triggered. The selection of the disconnection threshold must consider the trade-off between the nursing effort (i.e., the number of notifications for manual intervention) and the amount of time that no valid sensor readings are obtained. Figure 8(a) plots the number of alarms that our system would have triggered for different values of the disconnection threshold based on the data traces collected from the clinical trial. As expected, the system shows that as the disconnection threshold is increased, the number of alarms triggered per day is reduced. When the disconnection threshold is 3 minutes, the number of required interventions per patient is 9. This is comparable to the number of times pulse and oxygenation are manually measured in postoperative care. A disconnection threshold between



(a) Number of interventions



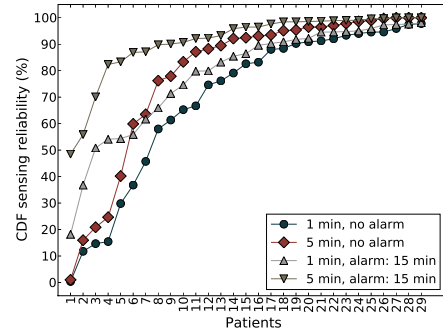
(b) Impact of alarms on sensing reliability

**Figure 8: Expected performance of a sensor disconnection alarm system**

10 – 15 minutes results in less than one intervention per patient per day. At this threshold value, our system significantly reduces the burden on the nursing staff compared to manual collection, which achieving a sampling rate two orders of magnitude higher than manual collection.

Figure 8(b) shows the impact of the alarm system on the sensing reliability. The sensing reliability values are computed as follows. Sensing outages longer than the disconnection threshold are identified. The system is penalized for the sensor failures during the time interval from the start of the outage until the disconnection alarm is triggered. The remaining time, from when the disconnection alarm is triggered until the end of the outage, is excluded from the recomputed sensing reliability.

The CDF of patient sensing reliability looks similar for different disconnection thresholds. The most pronounced differences are for patients with reliability in the range 50% – 75%. As expected, the best sensing reliability is obtained when the disconnection threshold is set to its lowest value of 5 minutes, but increasing the threshold interval has only a small impact on sensing reliability. Outside the reliability range 50% – 75%, the impact of the disconnection threshold is negligible. This shows that disconnection thresholds in the range



**Figure 9: Combining oversampling and sensor disconnection alarm systems**

10 – 15 minutes results in desirable balance between sensing reliability and intervention cost.

**Result:** *Disconnections may be mitigated through an automatic alarm system with low alarm rates.*

In the following, we estimate the potential benefit of combining oversampling and the disconnection alarm system to achieve even better performance. First, we consider the base case when the sensing requirement is one sample per minute. As previously discussed, reducing the sampling requirement to a sample every 5 minutes results in significant reliability improvements for most patients (see Figure 9). Similarly, incorporating an alarm system with disconnection threshold of 15 minutes also results in reliability improvements. Comparing these two curves (*5 min, no alarm* and *1 min, alarm: 15 min*) shows that the two mechanisms act in different ways. The sensor disconnection alarm system has the most impact on patients with low reliability (i.e., those that had disconnections) while the oversampling mechanism handles intermittent sensing errors. Combining the two mechanisms results in significant improvements: only 3 patients had lower than 80% sensing reliability when the measurements are required once every 5 minutes and a disconnection threshold of 15 minutes is used. From the three patients whose sensing reliability was below 80%, we obtained less than 7 minutes of valid measurements. These makes their reliability unrepresentative for the case when an alarm system would be employed.

**Result:** *Oversampling and disconnection alarms are complementary and can be combined to achieve further improvement in sensing reliability.*

#### 4.4 Detecting Clinical Deterioration

Systems for automatically detecting clinical deterioration may improve patient outcomes by allowing doctors to intervene before a patient’s condition worsens. While we have not integrated our system with an automatic scoring system, preliminary results indicate that the developed patient monitoring system provide suffi-

cient resolution to detect clinical deterioration. During the trial, two patients suffered from clinical deterioration and were transferred to the ICU. The pulse and oxygenation data reported by our system are shown in Figure 10. Clinical deterioration is visible in patient 3 (see Figure 10(a)). Upon being admitted to the unit, the patient had a average heart rate of 55 beats per minute. By the time the patient was transferred to the ICU, the heart rate dropped to 35 beats per minute. A slight degradation in oxygenation is also present. Due to the abrupt deterioration in the patient’s condition (about 2 hours), it is likely that his/her vital signs would not have been measured in a unit which does not poses monitoring equipment.

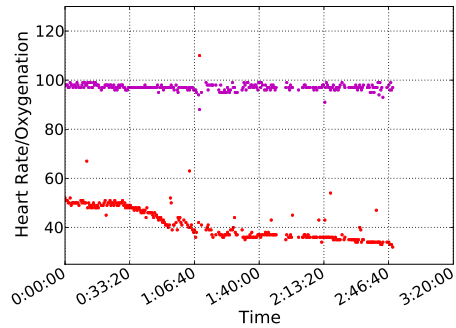
Figure 10(b) plots the pulse and oxygenation readings from patient 11. The patient was monitored for 15.4 hours before being transferred to the ICU. During this time, several correlated increases in heart rate and decreases in pulse and oxygenation occurred. In fact, the system provides sufficient resolution to correlate these events such that an automatic clinical deterioration system could have triggered an alarm. These examples highlight that the devised system provides sufficient resolution for analyzing trends in heart rates and pulse oxygenation. As part of our future work, we plan to integrate the patient monitoring system with an automatic scoring system.

**Result:** Preliminary results show that the system has sufficient resolution for detecting clinical deterioration.

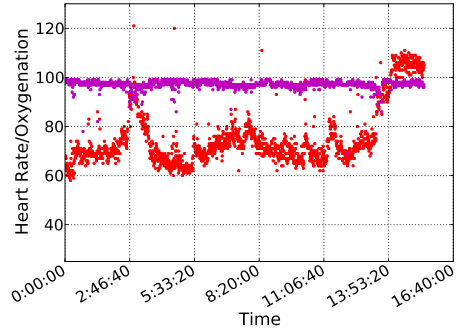
## 5. DISCUSSIONS

**Relay Redundancy:** The need to ensure network coverage within the step-down unit was one of the concerns raised during the planning of the clinical trial. We considered the possibility of minimizing the number of relay nodes necessary for ensuring coverage. However, this would have required performing in situ measurements to assess the coverage of the relays, which could have been a significant inconvenience to the care providers. Instead, we opted to deploy a redundant network of relays to ensure coverage. The architecture of the system which relies on mesh networking and the availability of power outlets in the hospital makes the deployment of the system effortless. It is worth noting that we were able to redeploy the entire system within 15 minutes. Relay redundancy was essential for tolerating the unplugging of the relays by the cleaning staff and the damaging of relays. Our data indicates that these failures did not impact adversely network performance. Moreover, it is unlike that any packet losses may be attributed to coverage gaps. In retrospect, adopting the more practical solution of deploying additional relay for redundancy was the right choice due the unexpectedly frequent relay failures.

**Existing Wi-Fi support:** Even though this pa-



(a) Patient 3



(b) Patient 11

**Figure 10: Pulse (red) and oxygenation (purple) measurements from patients which suffered clinical deterioration**

per focuses on reliability concerns, we have not yet discussed the most unreliable part of the system: the 802.11 wireless link from the base station to the hospital’s wireless infrastructure. The poor link quality often prevented us from logging into the base station to determine if valid readings were obtained from the monitored patients. Additionally, the transfer of large files was impossible due the same reason. In spite of these issues, we chose not to move the base station in order to maintain a consistent network setup.

It has been argued that a patient monitoring system should take advantage of existing 802.11 infrastructure. If the patient monitoring system would have been required to use this Wi-Fi link, the network reliability would have been significantly lower than that reported in this trial. It is worth noting that the IT department at Barnes-Jewish Hospital invested numerous man-hours to ensure “100% coverage”. However, Wi-Fi users are accustomed to having to change their location to achieve better performance and, as a result, there is little incentive to deploy more routers to provide true “100% coverage”. In contrast, in our system redundancy may be easily achieved and, with 802.15.4 technology, it comes at a low cost.

**Power Management:** During the clinical trial, patient nodes achieved a life time of up to 69 hours by

duty cycling the radio, sensor, and flash. This meets the maximum time we can monitor a patient per the agreement with the Washington University’s IRB. The radio and sensor duty cycle was measured on six nodes. The radio consumes 19 mA and had a duty cycle ranging from 0.12% to 2.09%. The sensor draws 24 mA and its duty cycle depends on the sampling rate. Existing pulse-oximeters take up to 8 seconds until average values for hear rate and oxygenation are reported. According, when the sampling rate is 30 seconds, we expect a duty cycle between 26.66% – 50.00%. On the observed devices we obtained duty cycles between 27.3% – 40.27%. Similarly, for a sampling rate of 60 seconds, we expect duty cycles between 13.33% – 25%. In the field, we observed duty cycles in the range 16.24% – 18.97%. These numbers indicate that sensing dominates the energy budget of the patient nodes. The obstacle in achieving lower duty cycles is the prolonged start-up time.

We believe that there are significant opportunities for further reducing the time the sensor is active. For example, a significant amount of energy is wasted when the patient node is left active while a patient goes for treatment outside the unit. A simple policy of reducing the sampling rate after multiple consecutive sensing failures could save significant energy. However, note that even without any of these more complex power management policies, we achieved a lifetime of 3 days. Interesting opportunities also exist for improving energy efficiency by using additional sensors. For example, accelerometers which have lower energy consumption than pulse oximeters, may be used to asses if a patient is moving. The detection of patient movement would prevent us from turning on the pulse oximeter sensor when it cannot provide valid readings and waste energy as a result. The cessation of patient movement would constitute a trigger for the start of measurements.

## 6. CONCLUSIONS

This paper presents the design, deployment, and evaluation of a wireless pulse-oximetry monitoring system in a hospital unit. the study presented in this paper involves real patients monitored by a large scale system over a long period of time. The patients were monitored in situ to realistically assess the feasibility of WSN technology for patient monitoring. The system we deployed had 18 relay nodes and required multi-hop communication for data delivery. As part of the study, we monitored 32 patients recruited over six months for a total of 31 days of continuous monitoring. Our work made several main contributions to wireless sensor network technology and clinical monitoring. (1) Our network achieved a 99.92% median reliability over 31 hours of monitoring. The high network reliability indicates the feasibility of applying wireless sensor network technol-

ogy for clinical monitoring and the efficacy of separating end-to-end routing from first-hop relay association in a clinical environments. (2) System reliability is dominated by the sensing reliability of the commercial pulse oximeter. Sensing failures are frequent, but usually occur in short bursts with the exception of prolonged sensor disconnections. Oversampling and disconnection alarms that can substantially enhance sensing reliability. (3) Our study provides clinical examples that show the potential of wireless clinical monitoring system in enabling real-time detection of clinical deterioration in patients. A promising step towards real-time clinical detection systems for general hospital units, our work also points to several important future areas of research, such as the integration of real-time clinical monitoring systems with the electronic health record systems and the development of clinical event detection algorithms based on real-time sensor streams.

## Acknowledgment

The project described was supported 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.

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