Implementation of a Cyber-Physical System Using Wireless Sensor Networks for Monitoring Patients

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Abstract—Sensing, distributed computation and wireless communication are the essential building components of a Cyber-Physical System (CPS). Having many advantages such as mobility, low power, multi-hop routing, low latency, self-administration, autonomous data acquisition, and fault tolerance, Wireless Sensor Networks (WSNs) have gone beyond the scope of monitoring the environment and can be a way to support CPS. This paper presents the design, deployment, and empirical study of an eHealth system, which can remotely monitor vital signs from patients such as body temperature, blood pressure, SPO2, and heart rate. The primary contribution of this paper is the measurements of the proposed eHealth device that assesses the feasibility of WSNs for patient monitoring in hospitals in two aspects of communication and clinical sensing. Moreover, both simulation and experiment are used to investigate the performance of the design in many aspects such as networking reliability, sensing reliability, or end-to-end delay. The results show that the network achieved high reliability - nearly 97% while the sensing reliability of the vital signs can be obtained at approximately 98%. This indicates the feasibility and promise of using WSNs for continuous patient monitoring and clinical worsening detection in general hospital units.

Index Terms—Wireless Sensor Networks, patient monitoring, eHealth, Cyber-Physical System.


In most hospitals, clinical deterioration in patients in hospitals is a major concern. As reporting in [1,2], 4% – 17% of the inpatients suffer from adverse events such as cardiac or respiratory arrests. In [4], a retrospective study shows that nearly 70% of such events could have been prevented. Hence, in order to improve patient outcomes, a key factor is to detect clinical deterioration as early as possible so that the patients can be intervened before their condition worsens. It is possible to detect the clinical deterioration because most patients exhibit changes in their vital signs hours prior to an adverse event [5]. There are many automatic scoring systems which are developed to identify clinical deterioration in patients based on their vital signs [6,7]. However, the population that would most benefit from the early detection of clinical deterioration is in general or step-down hospital units. In such units, the vital signs of patients are usually measured manually during a long time. For example, in postoperative care, nurses measure the vital signs only 10 times during the first 24 hours following an operation [8]. This could result in a prolonged delay until clinical deterioration is detected. Thus, it is necessary to develop a monitoring system to collect the real-time vital signs of patients in hospitals. However, collecting patient vital signs raises unique challenges that are poorly addressed by existing commercial telemetry systems. Different from cardiac or epilepsy care, which requires high data rate EKG, EEG, or acceleration measurements, the monitoring of vital signs requires low data rates. Hence, WSNs based on the IEEE 802.15.4 standard can be a better candidate than Wi-Fi networks based on the IEEE 802.11 standard because of the following reasons.

Firstly, at low data rates 802.15.4 radios are more efficient than 802.11 in terms of energy consumption. This helps patient devices using 802.15.4 radios have a longer battery life. The nursing staff is routinely overloaded and the bothersome and error-prone process of changing batteries may interfere with their primary function providing care. Second, the results from the clinical trial indicate that sensing was the primary source of unreliability and that, at the low data rates required by vital sign monitoring, WSNs are already highly reliable with the Packet Reception Rate of 98% [9,10]. Therefore, the minor gains in network reliability that may be achieved by using a well-engineered Wi-Fi network would only improve system reliability marginally.

Third, the cost of deploying a mesh network consisting of wireless sensors is lower than that of installing a Wi-Fi system since WSNs are self-organizing networks. Therefore, the cost of adopting a patient monitoring system in a hospital without Wi-Fi infrastructure is lower than that of existing commercial systems.

Finally, WSNs may be deployed on demand. This flexibility may be important for hospitals which do not have sufficient resources to monitor all hospitalized pa-
tients. From all of issues mentioned above, the design of an eHealth system in hospitals that can monitor primary vital signs (including body temperature, blood pressure, heart rate, SPO2) of patients is necessarily critical.

2. Related work

There are many systems which have been developed for measuring a patients physiological state. These systems employ various wireless technologies: Wi-Fi [11,12,13], cellular network [14,15], and WSNs [16,17]. However, in this paper only systems using sensor network technology are focused due to its energy efficiency and ease of deployment. Upto now, WSNs have been developed for elderly care [17], disaster recovery [13,14,15], and clinical monitoring [11,18,12]. The basis function supported by these systems is to monitor patient vital signs. Code Blue focuses on disaster response applications and uses a publish/subscribe system to support many-to-many communication [19]. The AlarmNet project implements the data collection from mobile and static sensors through a query service [17]. MEDiSIN [18] project independently developed similar network architectures: stationary relay nodes are deployed to ensure connectivity between a patient worn sensor and a base station. The MEDiSIN and SMART [20] projects focus on monitoring patients waiting in emergency rooms. In [18], 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. Different from those related works mentioned, the design of proposed eHealth system in this paper improves several advantages from those projects:

- Our design does not need to use the relay nodes as in MEDiSIN. Because vital signs are transmitted at low data rate, hence every sensor node can be both a transmitter and a relay/forwarding node without decreasing the data rate of each transmitting node.
- The proposed hardware device can work in WSNs deployed in hospital for inpatients. Moreover, if patients stay at home and need monitoring vital signs, the patient device can transmit collected data through cellular networks (GSM/UMTS) to the centralized station as in AlarmNet.
- The routing protocol used with the eHealth system can support the slow movement of patients while it can ensure a high reliability of data transmission.

Many vital signs can be collected by the proposed patient device: body temperature, SPO2, heart rate and blood pressure (systolic and diastolic).

3. Proposed design of a clinical monitoring system

This section describes the proposed system architecture, hardware design, and software components that are developed for the patient monitoring system.

3.1. System architecture

Our monitoring system (eHealth) consists of a base station (eHealth Gateway) and many sensor nodes (eHealth nodes) that form a wireless sensor network. The eHealth Gateway runs an application that can collect the vital signs from each eHealth node attached to a patient. Moreover, this application can manage or control the operation of the eHealth node such as changing the sampling rate or adjust the transmission power level. As mentioned previously, the eHealth node can also act as a relay node that can forward the collected data from other nodes in the network.

The delivery of patient data involves multi-hop communication of the deployed WSN. Hence, the system has some notable features. Firstly, the monitoring system does not need the relay nodes attached to the wired network of hospitals. Therefore, the deployment cost of our system will be lower because it will not need any cable installation. Second, in contrast to other habitat monitoring system, our system can use the power supplied in hospital outlets or external battery for operation. This can increase the flexibility of system deployment.

Finally, the proposed architecture supports the movement of patient with slow speed (approximately 3m/s) by using ODEUR+ routing protocol [9]. ODEUR+ is a proactive routing protocol, which periodically broadcasts the beacons from the sink (or gateway) to the sensor network so that other nodes can build the routing tree to transmit the data packets. It uses a parameter called Mobility Gradient calculated from continuous RSSI values between sensor nodes to detect the movement direction of nodes. From this MG and RSSI values, each node can choose the best neighbor node to forward data packets.

3.2. Hardware

Our developed eHealth node consists of two parts: data collecting module (DCM) and RF communication module (RCM). Each module will be described in the following sections.

3.2.1. Data collecting module (DCM)

The block diagram of this module is shown in Figure 1. It consists of a TI MCU MSP430F6659 with 512 KB code memory and 66 KB SRAM for data processing and can be powered by an external supply of 5V-9V. Besides, this module has several interfaces which can get the vital data from the blood pressure device SANITAS SBC27 [21], SPO2 and heart date from AVAX AV-50DL device [22] and body temperature from a sensor DS18B20 [23]. Other equivalent measurement devices can be used with this DCM. Moreover, this module can also collect ECG signal. For display purpose, a LCD is integrated in this module to show the information of device operation and collected data. All the collected data can be also logged to SD card for later analysis. In addition, one UART interface is used to bridge the collected vital signs from measurement.
devices to RF communication module for transmission to the data center via the deployed WSN. For operation, this module also needs to run our embedded application, which is designed to target low power consumption.

3.2.2. RF communication module (RCM)
The popular TelosB mote [30] is used as a RF communication module (RCM), which is connected to the DCM and powered by DCM as well. Each TelosB mote has a 16-bit RISC processor with 48 KB code memory and 10 KB RAM. Wireless communication is provided using a Chipcon CC2420 radio chip compatible with IEEE 802.15.4. The radio operates in the unlicensed 2.4GHz band and provides a raw bandwidth of 250 kbps. Similar hardware capabilities have been developed and used as part of AID-IN [14], MEDIiSN [18], SMART [20], ALARMNET [17] and WIISARD [24] projects. To aim the low power consumption, especially in radio transmission, this RCM runs our designed embedded application built on TinyOS for sensor networking with low-power listening protocol B-MAC [25]. Moreover, the ODEUR+ routing protocol [9] is also implemented in this application to support multi-hop routing and mobility for WSNs. When receiving the data (vital signs) from DCM, RCM will transmit it to the eHealth Gateway using multi-hop communication thanks to ODEUR+ protocol. The eHealth Gateway is also a TelosB mote but it does not have the DCM connected to itself.

The completed hardware design of eHealth sensor node with all measurement devices is shown in Figure 2, which includes: blood pressure measurement device, SPO2 and hear rate measurement device and body temperature sensor. However, due to the low-data rate of WSNs, the ECG signal is only stored in an SD card for further medical analysis without transmitting over WSN.

3.2.3. Data visualization
For visualizing the data, the user-defined WiseCoMaSys software [26] (shown in Figure 3) is modified to collect vital signs from each eHealth sensor node attached to each patient. This software connects to the eHealth Gateway node to receive the data packets containing vital signs from other nodes. In addition, this software can also control the operation of each eHealth node based on a set of rich features from this software such as changing the operation of eHealth node, displaying real-time data, logging data for analysis or setting alarm for any unexpected vital signs collected.

3.2.4. Timing Synchronization
Time is a very important factor in data collection services. Hence, every data packet (containing vital signs) reported from each eHealth node to the data center needs to be embedded with a timestamp. Therefore, the global time synchronization of the whole sensor network is required. Moreover, due to the low data rate, the resolution of one second is enough in most monitoring applications [27] [28] [29] which have the data period of several minutes. In order to reduce the overhead exchanged in the whole network, simple time synchronization is used with ODEUR+ protocol utilizing the beacon exchange mechanism. In the proposed system architecture, a eHealth gateway will keep a clock source which can be updated from a management software WiseCoMaSys running in the gateway. Each beacon
will carry a 32-bit compressed label of time originated from the sink to the entire network. Each local node also has a local timer running separately and this timer will be updated after that node receives a beacon and extracts time information in that beacon. Hence, global time synchronization can be well performed if the delay of MAC and PHY layers is negligible. Moreover, the WiSeCoMaSys is usually connected with a gateway to communicate with the deployed WSN. Therefore, it can compare the time header in each receiving packet and the system time to decide whether a time update is needed.

4. Performance evaluation

To investigate the feasibility of deploying a WSN for patient monitoring in hospitals, both simulations and experiments are performed for evaluation to answer the following questions:

- How reliable is the monitoring system in the networking aspect?
- How reliable are the collected vital signs?
- How can the system support the mobility?
- How does multi-hop communication affect to the data transmission?

4.1. Simulation results

In order to investigate the operation of the sensor networks with the proposed eHealth devices in case of dense networks, TOSSIM simulator [33] is used to evaluate several parameters because the RDM is implemented in TinyOS for wireless communication, which is fully supported by TOSSIM. In order to simulate a deterministic sensor network with mobility of nodes, a WSN with 21 nodes laid out in a basic grid of 100m x 100m is shown in Figure 4, which can simulate 21 patient beds in one hospitalized room. Each bed is attached to eHealth sensor node for patient monitoring. Each cell of the grid has the size of 20m x 20m. The effective distance for communication between two TelosB nodes (RCM) is approximately 70m to 100m [31]; hence, in this case, the distance between the nodes is 20m, which forms a high density of nodes, which can generate much traffic in the network. In this scenario, only one node (patient bed) is moving. The moving node having address 20 is located at position (90, 90) and can move along a given path at the speed of 2 m/s. The measurements are carried out at the sink or the gateway (node 0). Nodes are booted at a random point of time to avoid collisions. Each simulation is executed 5 times for each set of given parameters to find the optimum values of investigated parameters.

4.1.1. Data rate

In Figure 5, the data period is changed from 0.25 seconds to 60 seconds corresponding to high traffic and low traffic, and the beacon period of routing protocol is set at 4 seconds. The result shows that the maximum PRR is also approximately 98% when the data period is more than 2 seconds. This implies that if one needs a good transmission, the maximum data rate is about 0.5 msg/s (each message contains 42 bytes). When the data rate is above 0.5 msg/s, and with the periodical beacons, the total traffic in the network is rather high. This leads to frequent collisions because each node uses CSMA/CA at the MAC layer. The reasons of packet loss will be discussed in the next sections.

4.1.2. Packet Reception Rate (PRR)

Packet Reception Rate (PRR) is a parameter used to measure the network reliability. It is the ratio of the number of received packets at the gateway over the number of sent packets from the sending node. Figure 6 illustrates the simulation results in three cases in the simulation area of 100m x 100m with the following settings:

- All nodes are static.
- The sink node is static and located at (0, 0). Only node 20 moves along a given path, beginning from the position (90, 90).
- Node 20 is static and located at (0, 0) and the sink node moves along a given path, beginning from the position (90, 90).
- The speed of the mobile node is set at 2 m/s.
- The data period and beacon period is 5 and 4 seconds respectively.
This figure also shows the PRR of the moving node (sink or sensor node) at the speed of 2m/s. It can be seen that in most of the cases, the total average PRR within the network is more than 85% at the given moving speed, and the moving node has a lower PRR (node 20). Figure 6 also shows that the border nodes (e.g., node 4, 9, 14) have a lower PRR than the others while the nodes near the sink (e.g., node 1, 2) have excellent PRR (approximate 97%).

4.1.3. Packet loss
The loss of packets in the network depends on the radio signal strength and the loss in the buffer of a local node when the packet arrival rate is greater than the processing rate. To measure the buffer loss of each node, the number of incoming packets and outgoing packets are counted to give the number of lost packets. Figure 7 shows that in all nodes of the network, the buffer loss is relatively small (under 1.5%) in most cases. Again, this is because buffers of traffic flows are separated. From this result, with such a low packet loss in buffers, it can be concluded that the packet loss is mostly because of the signal propagation. By default, each local node has an input queue and an output queue with the size of 10 packets.

4.2. Experiment results
To investigate the validation of the eHealth system in reality, 10 sensor nodes are used to deploy a live WSN with one gateway (GW) to monitor patients condition inside a hospitalized room, (shown in Figure 8). In this network, there are 2 eHealth nodes (node 1 and node 2) with devices to collect vital signs, other nodes are configured to transmit the data packets without vital signs. All the data packets from all nodes is recorded in 2 hours for analysis.

4.2.1. Packet Reception Rate
After analyzing the data logged during 2 hours, the results in Figure 9 show that the PRR of each node is rather good. Most of the nodes have the successful delivery rate of approximately 99%, which indicates that the networking component provides high reliability and demonstrates the robustness of the ODEUR+ routing protocol. Moreover, nodes with more hops (node 2 and node 4) have a lower PRR than other nodes with 1 hop.

4.2.2. Sensing reliability
Sensing reliability is also an important factor, which is the fraction of packets delivered to the gateway that has valid readings (e.g. heart rate, SPO2). In our system, the invalid readings are usually affected by the patient movement, sensor disconnection or sensor placement as reported in [31]. Patient movement including movement of arms on which the blood pressure device is places, finger tapping or fidgeting can lead to invalid readings. The heart rate collected from eHealth node 1 and 2 attached to 2 tested persons is illustrated in Figure 10. In this figure, it can be seen that there are some invalid
Fig. 10: Heart rate and SPO2 monitored from 2 persons attached with eHealth node 1 and node 2.

Fig. 11: PRR of networks versus duty cycle.

Fig. 12: Network depth of 22-node test-bed.

Fig. 13: PRR versus hop-count.

reading of SPO2 (red circles). The invalid reading ratio of eHealth nodes in the experiment is less than 2% (maximum 11 invalid readings of total 565 readings). It indicates the sensing reliability of the eHealth devices during the measurement and radio transmission.

4.2.3. Duty cycle

Because the energy consumed for radio transmission is much more than data processing inside the DCM and RCM [32], the duty cycle of RCM is changed to investigate how it can affect to the PRR of the deployed WSN. The results displayed in Figure 11 conclude that even though the duty cycle of nodes is reduced to 50% (which means less energy consumption), the PRR of the network still keeps good enough for data delivery at PRR of 94%. However, when the duty cycle is reduced to 10%, the packet loss rate is approximately 25%. Besides, the end-to-end delay of data packets in the deployed experiment is around 1 second, which is good enough for transmitting packets at the maximum data rate of 0.5 message/s mentioned in section IV.2.

4.2.4. Network scalability

In order to investigate the network scalability of our proposed design, a 22-node test-bed is set up with the same configuration of sensor nodes. The experiment is conducted in 2 hours and captured by WiSeCoMaSys to discover the connectivity changes between nodes. The investigation shows that the proposed design can support the network depth of 7 hops in this live WSN (shown in Figure 12) thanks to the ODEUR+ routing protocol. In addition, the average PRR values of all nodes are recorded during a running time of 2 hours to discover the relationship between PRR and hop counts (Figure 13). It can be seen that PRR of nodes decreases according to the increase of hop-counts. With the hop-count of 7 (node 11 shown in Figure 12), the PRR of this node is only 82

5. Conclusion

With the proposed architecture of eHealth device running an embedded application that collects vital signs from patients and have capability of radio communication, it is believed that this device can become a candidate in real-time wireless monitoring environment. The results in simulation and experiment proves that this eHealth device has a good PRR (nearly 97%) and sensing reliability (approximately 98%) with a set of parameters for configuration. This enables the support of CPS in wireless networking. In the future, the context-aware model can be integrated in this device to make the sensor node more advanced in patient monitoring by detecting the dangerous range of the collected vital signs.

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References


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