Patient Vital Signs Monitoring using Wireless Body Area Networks

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***Abstract*—Today hospitals are equipped with many electronic transmitting devices, which results in electromagnetic interference that may impair wireless transmissions between medical devices. On the other hand, reliable and continuous collection via wireless communications of patient vital signs such as blood pressure and flow, core temperature, ECG, carbon dioxide (CO_2) concentration is crucial for making real-time triage decisions. Hence, a novel wireless communication solution that seamlessly supports patient mobility and that prioritizes vital signs transmission using Wireless Body Area Networks (WBANs) is developed, implemented in TinyOS, and tested on Shimmer biomedical wireless sensor motes.**

I. Introduction

The rapid growth of wireless technologies enables continuous healthcare monitoring of mobile patients using compact biomedical wireless sensor motes. These small wearable devices - limited in memory, energy, computation, and communication capabilities - are deployed on a patient; then, they self-configure to form a networked cluster that is able to continuously monitor vital signs such as blood pressure and flow, core temperature, ECG, oxygen saturation, CO_2 concentration (for respiration monitoring). However, today hospitals are equipped with many electronic transmitting devices, which results in Radio Frequency (RF) interference that may impair wireless transmissions between medical devices. Still, reliable and continuous collection of patient vital signs via wireless communications is crucial for real-time triage, which is the process of prioritizing patients based on the severity of their condition.

Existing technology in the pre- and hospital environment lacks effective methods for prioritizing information streams, evaluating time-dependent trends, managing incomplete data, and providing effective alerts. Hence, we propose a novel wireless communication solution that - with minimum added RF interference - i) collects and prioritizes vital signs transmission using WBANs [1], ii) reliably transfers the acquired patient data to medical terminals or PDAs, and iii) seamlessly supports mobility as patients are moved along different hospital settings. Our solution overcomes the current limitations of patient monitoring in pre- and hospital environments, which represent an important barrier for developing improved trauma triage strategies.

Existing research on wireless healthcare systems have mainly focused on the design of one-BAN systems such as [2] (i.e., systems used on only one patient). While previous studies have proposed solutions to access patient healthcare data in real-time and provide emergency services [3], no solution has focused on prioritizing patient data transmission over the wireless channel by jointly considering 1) the patient condition and 2) the vital sign Quality of Service (QoS) requirements, e.g., end-to-end (e2e) delay and throughput.

Hence, to support real-time triage on multiple patients, in this work we propose a new interference-aware WBAN system that can continuously monitor vital signs of multiple patients and efficiently prioritize data transmission based on patient condition and vital sign QoS requirements. We assume that the patient condition is already diagnosed by the sensor-based system and, based on the condition (output of the triage process), a patient is categorized into one of the following three classes: "*Red*", "*Yellow*", and "*Green*", which indicate the level of treatment needed, i.e., *"immediate"*, *"delayed"*, and *"minimal"*, respectively. Based on the 'patient class', our solution aims at maximizing the transmission reliability[1] of vital signs while meeting their QoS requirements.

The remainder of this paper is organized as follows. In Sect. II, we present the proposed network architecture as well as the inter- and intra-BAN communication protocols. In Sect. III, we discuss the performance evaluation results and conclude the paper.

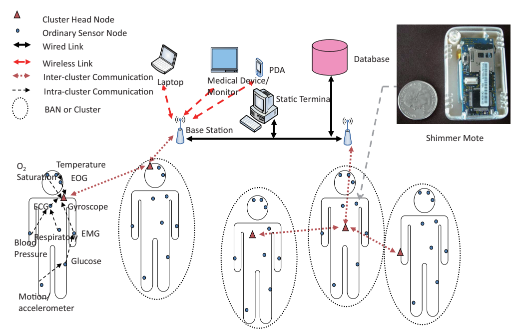


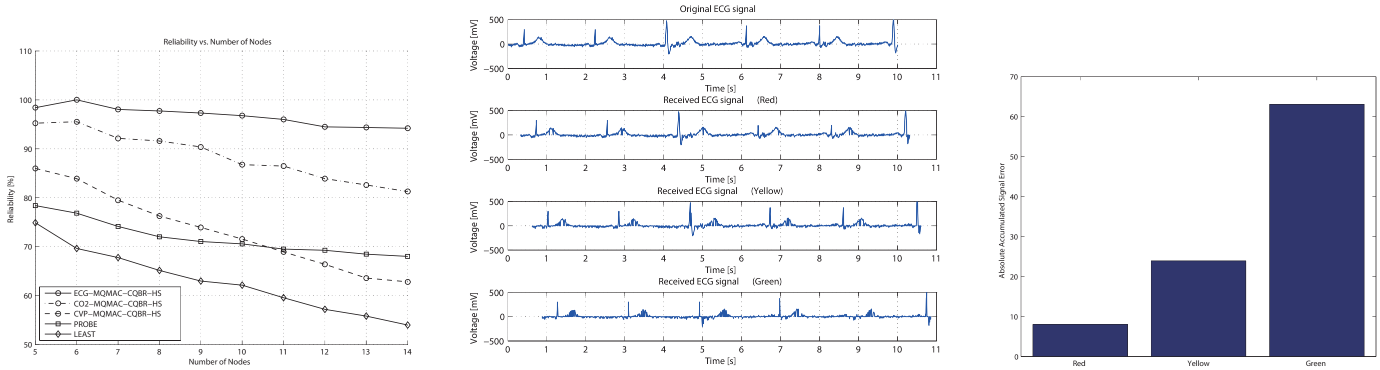
Fig. 1. Proposed Physical Network Architecture.

II. System Architecture and Communication Solution

The proposed networking system is designed to be a *two-tier hierarchical architecture* with the high-level tier composed of BANs (networked via inter-BAN communications) and the low-level tier composed of sensor nodes in each BAN (networked via intra-BAN communications). The *physical network architecture* is a two-tier hierarchical architecture composed of several clusters of sensor nodes deployed on a patient, each forming a body area network (Fig. 1). Every BAN is formed by wirelessly networked sensor nodes that monitor, collect, and pre-process patient physiological data. Inside each BAN, a distributed Cluster-Head (CH) selection mechanism is adopted in order to select a node with higher computing, energy, and networking capabilities to play the logic role of cluster head. This CH collects, aggregates, and fuses the data from other sensors in the cluster, performs data consistency check, and transmits via multihops the processed data to the best base station using other CHs (in different BANs) as relay nodes. The wireless station will then relay the data to a mobile terminal such as laptop, PDA, or medical device, or to a static terminal. Cluster heads, base stations, and mobile and static terminals can also forward each others' packets, share each others' patient information, and access a database - connected to the hospital backbone network - to obtain, if needed, the patient profile and medical history.

Our system is based on Shimmer motes (Fig. 1), small wireless sensor devices designed to support wearable biomedical applications. These wearable nodes provide an extremely extensible platform for real-time kinematic motion and physiological sensing. Each mote features a large storage capacity and low-power standard-based wireless communication technologies such as Bluetooth and ZigBee. A

[1] 'Reliability' is the ratio of the number of data packets received by the base station (a medical terminal) and the number of packets sent by a source node.



(a) End-to-end Packet Reliability. (b) ECG signals (Number of BANs = 14). (c) Error of the received ECG signals.

Fig. 2. Performance evaluation of our proposed solution.

Shimmer mote incorporates various sensors like triaxial accelerometer (which measures acceleration on x, y, and z axes), electrocardiogram (ECG), electromyogram (EMG), galvanic skin response (GSR), gyroscope (which measures the angular rate of motion), passive infrared (PIR), and tilt and vibration sensors.

The proposed two-tier architecture calls for *two different protocol stacks*, one for *inter-BAN* and the other for *intra-BAN* communications: the former provides communication between BANs, whereas the latter aggregates patient's vital signs inside each BAN. In order to exploit the ZigBee/Bluetooth co-existence capability, both interfaces may be used in our solution so that both inter- and intra-BAN communications can be supported at the same time. Specifically, as it takes longer to set up communications between mobile BANs using Bluetooth, we use Bluetooth for intra-BAN communications and ZigBee for inter-BAN communications (where the relative velocity of nodes attached to a patient is zero).

Inter-BAN Communication Solution: Our solution adopts a *cross-layer modular design*, which includes *Medium Access Control (MAC)*, *routing*, and *scheduling* functionalities: the MAC functionality is in charge of fairly and efficiently sharing the wireless resources and of granting medium access to each node with data to transmit; the routing functionality selects the best network path along which to send network traffic, and the scheduling functionality prioritizes data transmissions at a node, i.e., it decides which data packet is given first access to the channel.

Wireless sensor motes have the capability to select one of the multiple available frequency channels to communicate with each other. A *channel* is the 'portion' of the medium used to convey information from a sender (or transmitter) to a receiver. In our solution, the quality of channels is considered in the MAC and routing modules, which provides the foundation for our interference-aware Multi-channel Quality-based MAC (MQ-MAC) and Channel Quality Based Routing (CQBR) protocols. The quality of all the channels is estimated using a probing mechanism; using a two-way handshaking mechanism involving both the sender and the transmitted, the channel with the best quality is then used to forward packets. The channel quality is also considered in the routing module, i.e., paths with low quality links are not selected. Moreover, a two-level packet scheduling scheme is proposed to maximize the reliability for all three traffic classes while guaranteeing their e2e requirements. These software modules are also designed to be low complexity so that resource-limited sensor motes can run them.

Intra-BAN Communication Solution: The aim of the intra-BAN protocol is to keep the complexity low, to limit the processing overhead of the intra-BAN sensors, and to reduce the amount of interference generated. As the intra-BAN protocol starts, all the sensors in one BAN send out probing packets while their CH collects the transmission power information from these sensors, selects the best transmission power levels, and broadcasts one command packet requesting the sensors to adjust their transmission powers so that energy consumption and generated interference can be minimized.

III. Performance Evaluation and Conclusions

We implemented our solution on Shimmer wireless sensors and evaluated the system performance using indoor experiments performed in a building floor of about $50 \times 20\mathrm{m}^2$. Sampling of ECG, CO_2, and CVP blood pressure data (with low, medium, and high delay requirements, respectively) is emulated. The competing communication protocols considered are: 1) one-channel protocol without link quality information (LEAST), which routes packets along the shortest path; and 2) one-channel protocol with probing (PROBE), which routes packets along the path with the best route quality, i.e., the $\min\max$ link quality value of the links along a route.

Due to space limitation, partial experiment results are plotted here. The curves for our solution in Fig. 2(a) are denoted by 'X-MQMAC-CQBR-HS', where X represents the patient's data type (ECG/CO_2/CVP). Our solution is shown to have improved reliability over the other two protocols. This can be explained because our solution integrates a hybrid scheduler to guarantee e2e delay; also, by minimizing the generated interference and by selecting the best route (i.e., with best link quality), the e2e Packet Error Rate (PER) is reduced, thus achieving high e2e packet reliability. To see the effects of our solution on vital signs, we compared a sample of the received signals at the sink with the generated one in Figs. 2(b) and 2(c). From these two figures, a 'Red' patient experiences the least loss and delay, while a 'Green' patient has the largest loss and delay. Signal error due to packet loss is compared in Fig. 2(c). Note that the received signals are raw received data and signal processing techniques can be applied for better signal recovery.

Our solution offers better performance than conventional wireless communication protocols while guaranteeing low RF interference.

References

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