Quality of Service in Wireless e-Emergency: Main Issues and a Case-study

Óscar Gama[1], Paulo Carvalho[1], J. A. Afonso[2], P. M. Mendes[2]

[1] Informatics Dept., University of Minho, Braga, Portugal
{osg, pmc}@di.uminho.pt
[2] Industrial Electronics Dept., University of Minho, Guimarães, Portugal
{jose.afonso, paulo.mendes}@dei.uminho.pt

Abstract. Due to its critical nature, emergency healthcare (e-emergency) systems should be totally reliable, efficient and support real-time traffic. Therefore e-emergency networks must provide proper quality of service (QoS) levels. After assessing the relevance of QoS deployment in different e-health contexts, this paper presents a pragmatic case-study intended to be deployed in a hospital room containing patients with high risk abnormalities, whose vital signals are being monitored by personal wireless body sensor networks. After justifying the unsuitability of ZigBee standard in this e-emergency scenario, the use of Low-Power, Real-Time (LPRT) protocol for wireless sensor networks, is proposed as an adequate candidate for such task. For the present case-study, the protocol is able to fulfill quantitatively the required QoS levels.

Keywords: e-Health, e-Emergency, WSN, QoS, TDMA.

1 Introduction

An e-health system consists of a group of sensors attached non-invasively to a patient in order to sense the physiological parameters. It has been used in hospitals during the last decades using conventional wired equipment, hence not allowing the patient to move around freely. However, recent advances in wireless sensors technology are changing this scenario by permitting mobile and permanent monitoring of patients, even during their normal daily activities [1].

An e-health system should be able to accomplish at least one crucial aim: to monitor a patient and, when an emergency occurs, to trigger immediately an event to alert the patient and/or to warn a remote caregiver. In this way, both the patient and the caregiver can take timely the right procedure in accordance with the clinical episode. The system should also be able to trigger an alert anticipating the case where the patient is unaware of his/her health gravity. When a patient´s clinical state turn from a non-critical situation into a critical one, a context change occurs and consequently the healthcare network should adapt its performance requirements to the new situation. For instance, higher monitoring activity and lower delay transmission of the vital signals might be required when the patient´s clinical situation changes from non-critical to critical. Hence, healthcare networks should provide QoS facilities for e-emergency services, since these clearly demand for high reliability, guaranteed bandwidth, and short delays.

2 Vital Signal Monitoring

e-Health requires the monitoring of several vital signals simultaneously. The electrical characteristics of the vital signals usually used in emergency medical care are presented in Table 1 [2, 3].

At non-emergency medical situations, electrocardiogram (ECG) and blood oxygen saturation (SpO2) signals are usually transmitted in bursts, while signals such as body temperature and blood glucose, are transmitted in single packets to the base-station [4]. In fact, to reduce the traffic load and the power consumption of a body sensor network (BSN), the current trend in telemedicine systems is to enhance sensor node intelligence, available memory, processing power, and enabling on-line solicited requests only for results. In this way, continuous and bulky data transfer is sporadic, occurring only in intermittent occasions [4]. However in emergency cases this should not be the rule, since patient's life is priceless and above any other consideration. Continuous and bulky data transfer in real-time might be prevalent here.

Table 1. Vital Signal Electrical Characteristics

Vital signal (Hz)	**Freq. range** (Hz)	**Sampling rate** (Hz)	**Resolution** (bit)
ECG (per lead)	0.01…60-125	120-250	16
Temperature	0…0.1-1	0.2-2	12
Oximetry	0 … 30	60	12
Arterial pressure	0 … 60	120	12
Respiration rate	0.1 … 10	20	12
Cardiac rate	0.4 … 5	10	12

3 QoS Needs in e-Health

Some authors argue that differentiation based on data priority is inherent to wireless sensor networks (WSN), since it is normal to have sensors to monitor distinct physical parameters simultaneously, just as in BSNs. Here, the importance of the collected information is necessarily distinct, and therefore the network must prioritize the transmission of critical data when occurs a sudden clinical change in the patient. For example, in patients with cardiac diseases, heart activity information is more important than body temperature data. And depending on the patient´s clinical condition, the priority assigned to a vital signal can change dynamically. For instance, glucose data might be assigned a low priority when readings are in the normal range, but a higher priority might be reassigned to it when readings indicate hypo or hyper-glycemia.

Most current BSNs only offer the best-effort service, which is limitative for e-emergency support. In these networks, QoS provision is required to assist critical cases conveniently. This will enable, for instance, guaranteed bandwidth to higher priority streams for an efficient data delivery, even in case of fading or interference.

QoS control mechanisms are usually deployed in networks to guarantee consistent service levels concerning certain parameters, such as, packet loss, delay, jitter, and available bandwidth. These are the traditional end-to-end QoS parameters used to characterize the performance of communication infrastructures, including BSNs. For instance, the total delay of an ECG signal being displayed in the monitor should be less than 3 s for useful real time analysis by the cardiologists [5]; ECG signals require a minimum sampling rate of 250 Hz to guarantee that jitter does not affect the estimation of the R-wave fiducial point, which modifies considerably the spectrum [6]. No significant difference between ECG traces are detected by sampling the signal at rates between 250 and 500 Hz, but significant reduction in peak amplitude values and inaccurate interval measurements are obtained at 125 samples/s [4].

However, QoS in BSNs may not be fully described using only those parameters, because of its context-aware nature. For example, at application level, QoS may be regarded as guaranteeing the right number of sensors for monitoring the vital signals in accordance with the patients´ emergency state.

The available energy in the BSN is another very important parameter to take into account. In fact, if energy is carelessly consumed, the BSN may rapidly become completely useless due to lack of power. To prevent such failure, energy should be carefully saved using different approaches. For example, if the patient is in normal state then the sampling rate of sensors can be reduced to save power, or if the battery charge becomes low then its energy should be reserved to the more vital tasks of the patient. That is to say, the monitoring activity should adapt in accordance with the patient clinical state for energy saving. To save further energy, communication protocols should be simple, and data should be aggregated, eventually compressed, and transmitted in full-loaded packets, since computing demands much less energy than transmission. Attention must also be paid to delay, as it tends to increase linearly with the packet length.

Additionally, for efficiency reasons a large packet length may be chosen for non-critical situations. But as soon as an emergency occurs, the packet size can be reduced to meet the low delay QoS requirement, and signals considered irrelevant to this emergency episode are sampled at a lower rate, or not sampled at all.

Moreover, in emergency situations the computation power may be lowered to a minimum as all data must be forwarded, in opposition to the regular operation where, to save energy, the cardio-respiratory rhythm can be computed on-board before sending it. Or else, an ECG signal can be processed in the sensor itself to extract its relevant features. In this way, only information about an event is transmitted (e.g., QRS features and the corresponding timestamp of R-peak), hence reducing the traffic load and saving energy.

A BSN does not transmit only measurement data packets. Other packets may be present, such as those carrying control or alerting data. In this way, it is suggested that a high priority level should be assigned to data packets carrying alarming notification and measurements, and acknowledgement of correctly received packets; a medium priority level should be assigned to scheduled transmissions of data packets, and primary control packets (e.g. sensor configuration); and a low priority level should be given to periodic polling of nodes for network integrity check, and secondary control packets (e.g. link) [4].

Despite the number of e-health systems already developed [1], only a few encompass QoS support [7]. The QoS support and deployment provided in each project is diverse. Notwithstanding all the diversity, e-emergency systems should always support QoS in order to provide a pervasive, valuable and totally reliable assistance to any patient. This is the main goal in the case-study presented next.

5 Case-study

We are implementing an experimental testbed to deploy QoS solutions based on a real clinical scenario. The scenario under study is based on a hospital room containing six beds with one patient per bed. Each patient is monitored by a personal BSN, and one base-station (BS) collects the vital signals of all patients. The signals being monitored are temperature (T), oximetry (OXI), arterial pressure (ART), respiration rate (RR), and ECG data, as shown in Figure 1. Each signal is collected by a dedicated wireless sensor. Patient´s vital signals are analyzed and/or correlated at BS. Our goal is to develop a solution which guarantees that every signal is delivered to the BS with the appropriated QoS, as specified next.

According to IEEE 1073 group, a wireless ECG electrode should generate 4 kbps of data, and the latency introduced by framing the data samples and the transmission delay should be below 500 ms. Since ECG signals are the most demanding in terms of QoS, we take this value as the maximum delay that any vital signal should have. Continuous healthcare monitoring normally uses a three leads ECG device, composed of two active electrodes plus one of reference. Since research is being done to eliminate the reference electrode, we assume that each active electrode is implemented by a wireless sensor (ECG0, ECG1). So, according to Table 1, each BSN produces a maximum aggregated rate of 10.424 kbps, hence resulting that the maximum total traffic inside the hospital room is 62.544 kbps. Besides guaranteeing this minimum goodput and latency below 500 ms, the e-health system must also guarantee low packet losses to every vital signal, low energy consumption and balanced energy drainage in every BSN.

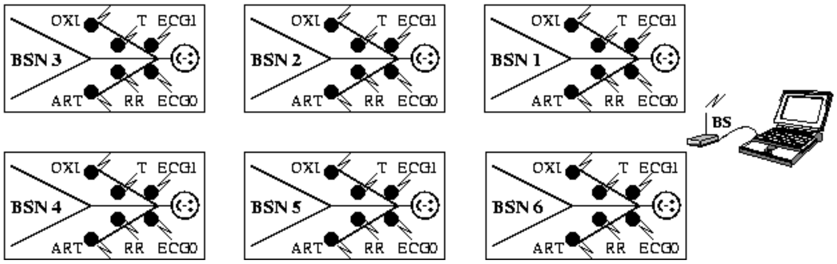

Fig. 1. Hospital room with a patient being monitored in each bed

In this case-study we have considered Bluetooth and ZigBee technologies. However, Bluetooth is unsuitable, since the protocol specifications allow a maximum of 7 active slaves (i.e. sensors) to be controlled by one master (i.e. BS).

ZigBee is a short range, low power, and low data rate standard for wireless sensor networks that supports a maximum rate of 250 kbps in the 2.4 GHz band. Therefore, a ZigBee WSN is able to handle the whole traffic generated inside the hospital room without congesting. Nevertheless, other factors which may affect QoS significantly have to be considered, such as the wireless channel access and transmissions errors. It is shown next why ZigBee is unsuitable for this case-study.

If traffic is to be sent within the same ZigBee PAN and short addresses are used, then a payload of 928 bits per packet is available to the applications. Ideally, all packets should be sent full-loaded in order to minimize the overhead for energy saving. Thus, to achieve the minimum required rate of 4 kbps, one packet carrying ECG data must be generated every 0.232 s. In addition, according to Table 1, each BSN should generate one full-loaded temperature data packet every 38.66 s, one oximetry data packet every 1.28 s, one arterial pressure data packet every 0.64 s, and one respiration data packet every 3.86 s. Since delivery delay must be below 500 ms, it is clear that only ECG data packets may be transmitted full-loaded.

Simulation results have shown that ZigBee is not adequate for several sensors to transmit ECG signals to a BS with full efficiency [8]. Either in acknowledged or in unacknowledged mode, the efficiency starts to drop when three or more ECG devices operate in the same RF channel. This is because ZigBee relies on CSMA-CA, a contention-based MAC protocol that is vulnerable to collisions. In acknowledged mode, lost packets may be retransmitted, but there is a maximum number (5) of retries allowed by ZigBee before declaring channel access failure. ZigBee seems to be more adequate for BSNs that do not have large amounts of data to transfer, only several small data packets per hour, like implanted medical sensors [9].

Another approach is using the beacon-enabled PAN mode described at IEEE 802.15.4 standard [10]. The BS sends regularly beacons which bound the superframes. These structures are divided into 16 identical slots. Any device wishing to communicate during the contention access period (CAP) shall compete with other devices using the slotted CSMA-CA. For low-latency applications or applications requiring specific bandwidth, the coordinator may dedicate portions of the active superframe to that application. These portions are called guaranteed time slots (GTSs). The GTSs form the contention-free period (CFP). The PAN coordinator may allocate up to seven of these GTSs, and a GTS may occupy more than one slot period. No transmissions within the CFP shall use a CSMA-CA mechanism to access the channel. The GTSs should be allocated dynamically to sensors accordingly with the QoS needs of the BSN. This TDMA-based transmission technique using slots is presently not available within any ZigBee profile.

Each full-loaded packet needs 4.256 ms to be completely transmitted at 250 kbps. Assuming that every packet is transmitted in individual slots, the beacon transmission interval must be above 4.256*16=68.096 ms. This means that the beacon order (BO) should be 3, implying a beacon interval of 122.88 ms (BI=3840*2BO bits, 0≤BO≤14). Note that the next BO (4) implies a beacon interval of 245.76 ms, hence making impossible to transmit a packet every 232 ms. There is a significant waste of bandwidth because the packet never occupies the whole slot duration. In this case (BO=3), only 55.4% of the slot period is used to send a full-loaded packet.

Since twelve ECG sensors are in the hospital room, and ignoring the maximum number (7) of GTSs imposed by the standard, only four slots would be available for the other sensors to send data. A CAP having four slots and 55.4% of slot period utilization may transmit at most 34625 bps. Comparing this value with 2424*6=14544 bps of data sent by all the remaining sensors in the room, it is expected a large number of collisions during the CAP, hence degrading seriously the QoS of the system.

In order to find an alternative to ZigBee standard, the asynchronous superpoll paradigm was considered. In this model, the BS sends beacons to each BSN following a round-robin pattern, specifying which data should be received from its sensors. The BS only polls the BSN, and not each one of its sensors. For example, suppose a BS send one beacon carrying this information: {dst 3, ecg0 2, ecg1 1, art 1, oxi 1, sleep 150}. All sensors belonging to BSN 3 receive the beacon and read that information. Then, sensor ECG0 sends immediately two consecutive packets, next ECG1 sensor sends one packet, arterial pressure sensor sends one packet and, finally, the oximetry sensor sends one more packet. All these packets are sent consecutively. After transmitting, each sensor sleeps for 150 ms. After receiving all packets, the BS sends a beacon with a new set of requirements to the next BSN to get the data of its sensors. With this schema, the channel is guaranteed to be free whenever a sensor is about to transmit, and each slot is fully utilized in terms of data capacity. Since packets length and slot duration may change, each sensor knows the right time to send data by counting the number of transmitted packets after the beacon reception. As soon as a beacon addressed to its BSN is received, a sensor must always be in listening state until it is scheduled to transmit, a phenomenon known as overhearing. Such situation leads to a wasteful and unbalanced energy drainage in the BSN.

Since the superpoll model is energetically inefficient, the LPRT beacon-based protocol was considered instead [11]. Besides presenting the advantages offered by the superpoll model in terms of slot utilization efficiency, LPRT may lead to an efficient WSN in terms of energy consumption. In this protocol, the superframe is divided in a fixed number (1024 by default) of mini-slots, and starts with the transmission, by the base-station, of the respective beacon frame, which is followed by the Contention Period (CP). During the CP any station can transmit non-real time traffic using the CSMA/CA algorithm. The CFP comes after the CP.

Transmissions and retransmissions during the CFP are determined by the base-station using resource grant (RG) information carried by the beacon frame. Beacons also carry acknowledgment feedback and eventually other information, such as, the clock time of the BS for synchronizing the network regarding timing measurements. All data frames are acknowledged. A retransmission procedure helps to increase the reliability of the protocol. Due to the real-time constraints, only one retransmission attempt is scheduled in case of transmission failure during the CFP. Data packets are sent in contiguous, fixed, mini-slots of the CFP, according to the RGs. Small guard periods must be used to avoid the superposition of adjacent transmissions. So, after receiving a beacon, each sensor is able to calculate the time it may sleep before and after transmitting. Hence, energy saving is achieved because sensors only have to switch on the transceiver to receive beacons and data, or to transmit data. Since CFP uses a TDMA-based schema to access the channel, low-latency is provided for transmissions in single-hop networks. The hidden node problem is absent during the CFP, although it may occur during the CP. If there are other similar e-health WSNs causing interferences over each other in the near rooms, then distinct operating channels should be selected for each WSN (16 channels are available at 2.4 GHz band). In LPRT, the slots are efficient and dynamically used, unlike the slotted IEEE 802.15.4, where the low-level of granularity of the time-slots leads necessarily to poor bandwidth efficiency.

In order to study the suitability of LPRT protocol for this case-study, let us consider that the beacon interval is 232 ms (this value should be below 250 ms to prevent retransmitted packets to have a delay above 500 ms). Then, each superframe contains at most, per BSN, two packets carrying each one 928 bits of ECG data, one packet with 5 bits of temperature data, one packet with 167 bits of oximetry data, one packet with 334 bits of arterial pressure data, and one packet with 55 bits of respiration rate data. Thereafter, each BSN sends altogether 2417 bits of data per superframe. Since the headers and trailer of each packet require 136 bits, the overhead for transmitting all data is significant: 33.8%. This inefficiency is caused by the different signal sampling rates and by the delivery delay constraint (< 500 ms). Since packets transmission should respect the LIFS period specified at IEEE 802.15.4 (0.64 ms) to guarantee that the MAC sub-layer of the BS is able to process all incoming packets, each BSN takes 16.8 ms in the superframe to send its data. So, the CFP should occupy 100.8 ms to accommodate the whole traffic produced by the six BSNs, leaving 131.2 ms for the CP. This time is enough to allow the association of a new BSN arrived at the room, making the system scalable to a certain degree. The association should be allowed by the BS only if the allocation of resources to the new BSN does not compromise the overall QoS of the system already established. By this analysis, we predict that LPRT protocol is adequate to be used in this case-study.

We have considered that all sensors are monitoring the patients at the highest sampling rates. However, such scenario should only occur in critical clinical episodes. In non-critical clinical situations, the sensors should monitor the patient at lower sampling rates in order to save battery energy and channel bandwidth. Such policy would also improve the scalability of the system. Therefore, self-reconfiguring each BSN in accordance with the patients´ clinical state is an important paradigm to follow. We believe that the LPRT protocol associated with the self-reconfiguration of the BSNs could produce very interesting results in terms of QoS and scalability.

6 Conclusions

e-Emergency systems should be totally reliable and efficient in order to provide a pervasive and valuable assistance to any patient with risk abnormalities. Therefore wireless e-emergency networks need to support QoS at distinct protocol levels, as they clearly demand for reliability, guaranteed bandwidth, and low delays, due to their real-time nature. Energy consumption should also be minimized to extend the lifetime of the BSN.

We have concluded that both Bluetooth and IEEE 802.15.4/ZigBee standards are unable to satisfy the QoS requirements of the presented case-study. The super-poll paradigm was also rejected because it is not energetically efficient. Instead, by analyzing the LPRT, a protocol for low-power, real-time WSNs, we have concluded that it is suitable to fulfill such QoS requirements. The use of LPRT leads to an e-emergency system with low power consumption, low latency, reliability, flexibility, and high-throughput efficiency. The traffic generated by the sensors can be transmitted free of collisions and the system may be scalable to a certain degree. Currently, we are implementing this model in a testbed for experimental analysis.

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