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Flexible Quality of Service (QoS) Model for Wireless Body Area Sensor Networks

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Wireless body area sensor networks (WBASNs) are becoming an increasingly significant breakthrough technology for smart healthcare systems, enabling improved clinical decision-making in daily medical care. Recently, radio frequency (RF) ultra-wideband (UWB) technology has developed substantially for physiological signal monitoring due to its advantages such as low power consumption, high transmission data rate, and miniature antenna size. Applications of future ubiquitous healthcare systems offer the prospect of collecting human vital signs, early detection of abnormal medical conditions, real-time healthcare data transmission and remote telemedicine support. However, due to the technical constraints of sensor batteries, the supply of power is a major bottleneck for healthcare system design. Moreover, medium access control (MAC) needs to support reliable transmission links that allow sensors to transmit data safely and stably. In this letter, we provide a flexible quality of service (QoS) model for ad-hoc networks that can support fast data transmission, adaptive schedule MAC control, and energy efficient ubiquitous WBASN networks. Results show that the proposed multi-hop communication ad-hoc network model can balance information packet collisions and power consumption. Additionally, wireless communications link in WBASNs can effectively overcome multi-user interference and offer high transmission data rates for healthcare systems.

1. Introduction: The number of patients with chronic ailments has increased significantly in recent years around the world. This is particularly true of elderly citizens who are more likely to suffer from chronic conditions that require a comprehensive healthcare system. A wireless body area network (WBAN) is typically defined as a specialized communication network that integrates a series of low energy consumption, affordable, and miniature sensors/devices positioned in, on or around the human body to enable the remote monitoring of the vital signs of patients. WBAN applications cover a wide range of fields such as sports, entertainment and human healthcare monitoring services [1]. The concept of a wireless body area sensor network (WBASN) is derived from the WBAN but unlike WBAN systems that require high mobility support, the WBASN sensors are commonly regarded as stationary. Also, no redundant sensors are available for WBANs, but WBASNs require additional sensors to be employed to compensate for possible failures. Moreover, WBANs are set up to monitor human activities using a periodic scheme at constant data rates, whereas WBASNs are widely deployed for application-specific monitoring that can be applied via sporadic time intervals [1]. WBASN sensors can collect vital signs in public places such as hospitals and offices or in urgent situations such as the scenes of fires and intensive care units. They can then transmit information to doctors/nurses via a gateway or remote medical server via the Internet. Implant sensors are located inside the human body and measure signals such as body temperature and pacemaker operation where the nature lossy environment of the human body might lead to significant signal energy attention. On-body sensors are usually put on clothes, trousers or even portable devices, which can gather heartbeat frequency, electrocardiograph (ECG) data and so on [2]. Sensor connectivity can be realized by introducing several radio frequency (RF) technologies such as Bluetooth, Zigbee and UWB. Although the first of these is a standard technology that is installed worldwide in over 2.5 billion devices and vehicles [3], its low mobility and on-body use only requirement make it unsuitable for smart medical healthcare applications. The second option, Zigbee, offers only a low data transmission rate of approximately 250 kbps, which means that it cannot support real-time in-body applications such as a capsular endoscope system requiring date rates of several Mbps [1]. Impulse radio ultra-wideband (IR-UWB) is a promising candidate for smart healthcare systems because it transmits pulses using simple modulation methods, and results in significant energy-saving. However, the high power consumption and complex circuitry of UWB receivers (Rx) prohibit its utilisation in energy restricted systems. In this letter, a smart gateway is proposed to replace the UWB Rx for energy saving purposes. Time hopping (TH) codes are studied to solve the ad-hoc network multiple user identity issue. Results in terms of collision probability and bit error rate (BER) performance show that the system can achieve satisfactory performance with a low energy cost. Additionally, the system can support high data transmission rates for multi-hop WBASN systems.

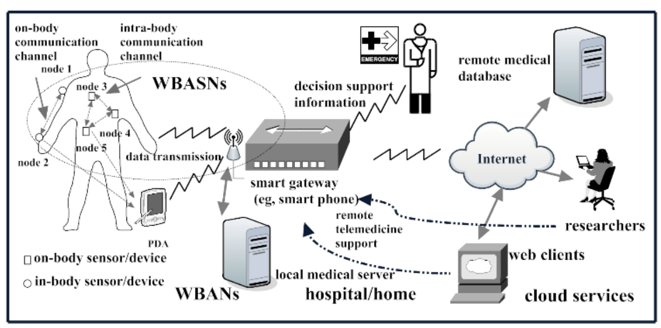

Fig. 1 *Structure of the real-time healthcare system*

2. WBASN Structures: As shown in Fig. 1, a WBASN system consists of one gateway, a series of sensor nodes and wireless communication links that can transmit patients' medical information to doctors and remote medical servers. The gateway, which refers to the Rx in the traditional network, sends a real-time warning message to the patients' doctor in an emergency situation. Smartphones as well as other personal digital assistants (PDAs) have been considered as information gateways because they can collect/process data from WBASN sensors and can provide personalized user interfaces [1, 3].

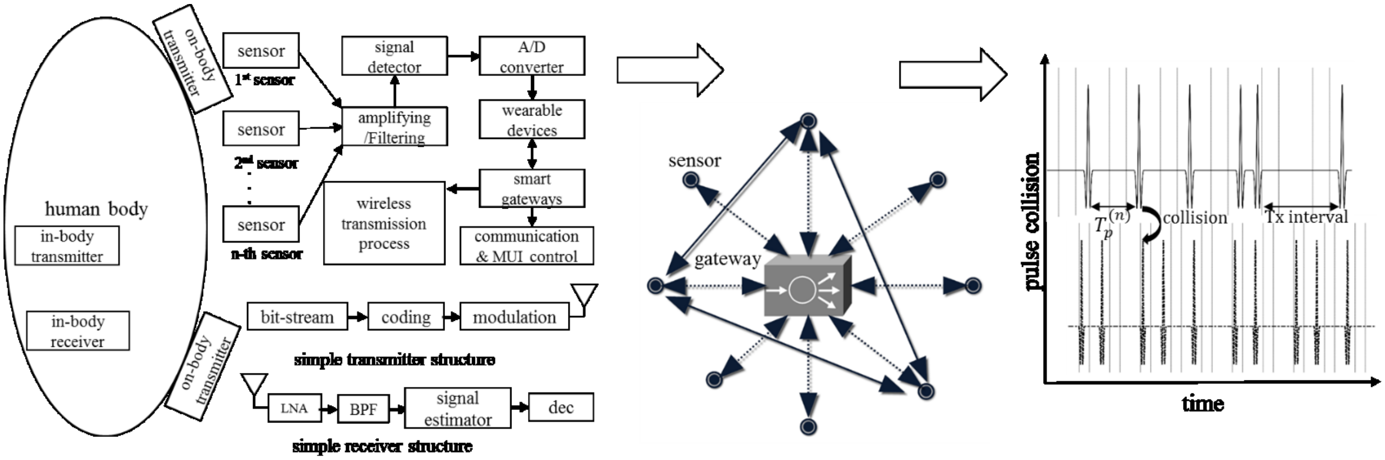

Fig. 2 *Overview of WBASNs system, sensor data information processing (left), ad-hoc network of sensors and gateway (middle), and the pulse collision process (right).*

As a result of battery technology limitations, it is less likely that sensors will measure data continuously because wireless transmission leads to high energy consumption [1]. In this letter, the TH coding scheme is applied to deal with emergency situations and interference between alert messages and regular information transmission. The MAC layer assigns unique time shift codes to priority emergency data that will not interfere with normal data transmission.

3. System model: Considering a realistic scenario with *M* patients in a hospital environment. The IEEE 802.15.4 standard physical layer [4] cannot adapt to multi-user interference so that it leads to inaccurate results. In this letter multiple pulses for one bit scheme and various pulse transmission rates are explored to allow the gateway to identify patients. It is assumed that every patient has *N* sensors attached to him/her. Based on our previous work [5], under the asynchronous UWB transmission scheme, the transmitted pulse position modulation (PPM) time hopping multiple access signal for *n*-th sensor of the *m*-th user can be defined as:

$$S_{m(n)}(t) = \sum_{j=-\infty}^{\infty} \sqrt{E_s} s(t) \qquad (1)$$

where $s(t)$ is expressed as:

$$s(t) = p(t - jT_s^{(k)} - c_j T_c - nT_p^{(m)} - \alpha_j^{(n)} \sum_{k=0}^{\infty} \varepsilon^{(k)}) \qquad (2)$$

and $p(t)$ represents the UWB waveform pulse, E_s is the pulse power and T_s is the time interval between successive transmissions with the *n*-sensors. The time-shift $c_j T_c$ is that caused by the TH code. One bit is transmitted using N_s pulses; $T_p^{(m)}$ is the pulse interval time for the *m*-th user. The PPM related parameters are ε the time-shift introducing by the modulation method and $\alpha_j^{(n)}$, the time delay that it introduces. Finally, $\varepsilon^{(k)}$ represents the asynchronous random time of the k^{th} sensor. The adaptive assignment method can make sure that the UWB-based WBASNs are able to assign unique multiple access parameters to different patients in the healthcare system. In [5], we demonstrated that PPM TH transmission is reliable and stable, and thus there is no need to offer feedback information or request that the Tx retransmits data in another time slot as a result of information loss. Detailed information concerning sensor information processing, and the structures of the Tx and Rx can be seen in the left portion of Fig. 2.

4. MAC protocol analysis: In this section, the characteristics of the MAC protocols are presented. The RF communication part of the sensors consumes the majority of the energy and thus needs to be taken into account [6]. The MAC protocol plays a key role in controlling the RF element as well as decreasing the energy consumption of the sensor nodes. Its essential tasks are controlling time delay and reducing the energy waste to prolong the system lifetime. Network coordination design is a challenge since numerous sensors may cause multi-user collisions and result in reduced reliability of the system.

As mentioned before, a constrained energy supply is one of the main challenges in a WBASN, so it is important to balance the energy consumption and the number of sensors or network performance. For simplicity purposes, we assume that all sensors have the same transmitting power P_t. According to the Federal Communications Commission (FCC) regulation, the maximum power level should be lower than -41.3 dBm per MHz [6]. It is clear that a collision will occur when more than one sensor belonging to the same user transmits information packets simultaneously. In this letter, the sensor nodes will stop working and switch to 'sleep mode' until they are assigned again to transmit new information data, thus lowering both energy consumption and the collision opportunities.

A wireless communication system inside or on the human body involves significant signal power attenuation. The detailed information concerning the path loss and energy calculations can be found in our previous work [7]. The minimal energy consumption for this process can be expressed as:

$$E_{Tx.min} = E_{elec} + E_{amp} d\alpha \qquad (3)$$

where $E_{Tx.min}$ and E_{elec} represent the minimal energy for a sensor to transmit energy to the gateway, and the minimal energy to activate the electronics, respectively; E_{amp} is the energy consumption of the transmitting amplifying process and d is the distance between the sensor and the gateway, with α being the path loss exponent. The essential energy consumption during the receiving process can be assumed to be $E_{Rx,ess}$, which is essentially $E_{Rx,ess} = E_{elec}$. The constraint of total energy that each sensor battery supplies E_{total} can be expressed as:

$$E_{total} \geq E_{Tx,min} + E_{Rx,ess} \qquad (4)$$

As can be seen from the right of Fig. 2, a collision may occur when more than one sensor node is transmitting information data simultaneously. In the literature [2, 8], authors have ignored this issue or treated the transmission as collision-free. To obtain more accurate results, an ad-hoc network methodology is introduced to deal with this situation. Since one bit is transmitted by N_s pulses, its transmission will be regarded as unsuccessful (collided with other transmitting pulses) when more than half of its transmitting pulses are overlapped. We assume that the probability of pulse collision between user *i* and *j* follows a binomial distribution. The BER of this condition can then be expressed as:

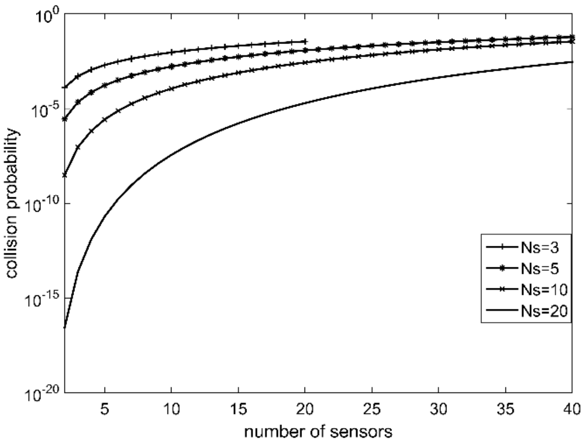

Fig. 3 *Number of sensors versus collision probability for different values of N_s under bit rate 30 Mbps.*

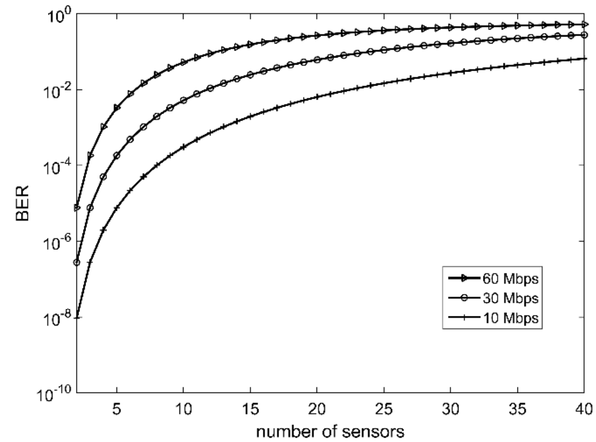

Fig. 4 *Number of sensors versus BER under different transmission data rate when N_s=10.*

$$BER = \sum_{i \geq [\frac{N_s}{2}]}^{Ns} P_1^i (1-P_1)^{N_s-i} \tag{5}$$

where P_1 is the average probability of error caused by pulse collision and results in random decision reception. P_1 can be defined as:

$$P_1 = \gamma P_2 \tag{6}$$

where $0 < \gamma < 1$, P_2 can be seen as collision probability among L active users:

$$P_2 = 1 - e^{-((L-1)\frac{T_p^{(n)}}{T_s})} \tag{7}$$

where T_s is the each pulse duration and $T_p^{(n)}$ is pulse interval between two successive pulses.

5. System performance: Based on the analysis above we now present the results obtained for the proposed network. Fig. 3 presents the collision probability versus the number of users for varying values of N_s using a bit rate of 30 Mbps. This shows that higher values of N_s can achieve better performance whilst as one would expect, the probability of collision increases when the number of users rises. Moreover, for an acceptable collision probability of 10^{-3} [5], the system can support approximately 35 sensors when $N_s = 20$ but only fewer than 5 sensors when $N_s = 3$. However, more energy will be expended when one single information bit is transmitted with a large number of pulses. To balance the energy consumption and system collision probability, we select $N_s = 10$ for further discussion.

Fig. 4 presents the system BER performance versus the number of users when employing data transmission rates of 60 Mbps, 30 Mbps, and 15 Mbps. The results indicate that the communication link can support fewer than 5 users at 60 Mbps but can almost 10 users of this is lowered to 15 Mbps. The wireless transmission system can naturally support more users at reduced data rates. Accordingly, the proposed method can balance energy consumption and system performance when compared to the majority of the up to date research work in the WBASN area. Although the advanced smart MIMOSA RFID sensor network that can minimizes energy consumption by introducing modular architecture design, the maximum data rates are limited to 100 kbps and thus cannot support m-health and remote telemedicine applications [9]. In [10], the proposed wearable ECG healthcare monitoring WBASN technology which was implemented using a wavelet transform digital signal processing circuit can achieve lower power consumption. However, the sophisticated structure of synthesizer transceiver for multi-channel bio-signal acquisition makes adaptive fuzzy resolution control approach that can reduce transmission energy for WBASN is presented in [11] this operates at the expense of throughput and lower QoS. In [2], the reported GPS-based Bluetooth healthcare monitoring technology is not suitable for future applications due to its low indoor accuracy performance. The proposed flexible quality of service (QoS) model for WBASNs has been analysed under conditions that approximate a realistic hospital scenario with a multi-user environment. To achieve a lower BER performance, the transmit power could be increased, which leads to higher energy consumption. The results indicate that the system supported a wide range of BER performances under the multiple pulses per bit scheme. This approach can be deployed to future customized QoS services for application-specific smart healthcare monitoring systems in terms of data rates and energy consumption.

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