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PERFORMANCE ANALYSIS OF THE IEEE 802.15.4 BASED ECG MONITORING NETWORK

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ABSTRACT

The integration of biomedical sensors with wireless network technology may have great potentials in medical applications. In this paper, we investigate the use of the IEEE 802.15.4 standard in an ECG monitoring sensor network and study the effects of CSMA/CA mechanism, number of network devices, sampling rates and transmitting cycles. The performance of the network is analyzed in terms of transmission delay, end to end latency, and packet delivery rate.

Both biomedical signal sampling time and transmission delay contribute to the end to end latency, but the end to end latency is mainly introduced by signal sampling time, especially for low data rate biomedical sensors. The packet delivery rate increases when the number of payload data becomes large due to high channel efficiency and packet coding efficiency, but large size packet suffers high end to end latency. In our case study, for a full size MAC packet with maximum payload size (114 bytes), the average end to end latency introduced by sampling and transmitting is about 90 ms. For time-critical applications, a payload size between 40 and 60 bytes can be a good choice, due to lower end to end latency and acceptable packet delivery rate. In the design and deployment of biomedical sensor networks in time-critical medical care applications, trade-off between end to end latency and packet delivery rate must be considered.

KEY WORDS

Wireless sensor networks, IEEE 802.15.4, ECG, performance analysis

1. Introduction

The IEEE 802.15.4 standard is targeted to low power, low data rate wireless network applications, such as wireless body area network (WBAN), home automation and environmental monitoring network. One of its promising applications is in medical care. In advanced hospitals, light-weight and battery-operated sensor nodes equipped with an array of biomedical sensors can be attached to a large number of patients monitoring physiological data and vital signs. Examples are body temperature, blood pressure, electrocardiogram (ECG), electroencephalogram (EEG), Pulse Oximeters (SpO2) and heart rate, which are sensed and transmitted to the medical center, where these data could be used for health status monitoring and further analysis. The biomedical sensor network becomes helpful in providing the freedom of movement while ensuring that the patients are continuously monitored and cared for.

The biomedical sensor networks are usually used to monitor patients-in-risk health status. Therefore the performance of the network is much more important than in other applications. Specific requirements, or a minimum set of quality of services (QoS), must be satisfied.

In [1], the maximum data throughput and minimum transmission delay of the IEEE 802.15.4 standard are studied by mathematical analysis and experiments, but only one sender and one receiver network is studied in this paper. In [2], the performance of the IEEE 802.15.4 is analyzed for medical sensor body area networking. The analysis mainly focuses on long-term power consumption of sensors. The performance of the IEEE 802.15.4 network for medical application is evaluated by simulation in [3], a star network with up to 16 transmitters is investigated, the impact of interference is also studied in this paper. However, analysis on transmission delay, end to end latency and packet delivery rate of biomedical sensor networks is still insufficient.

In this paper we study the effects of Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA) mechanism, number of network devices, sampling rates and transmitting cycles. The performance metrics, including transmission delay, end to end latency, and packet delivery rate are analyzed. An IEEE 802.15.4 standard based ECG monitoring network is investigated as a case study. By varying the payload size, sampling and transmitting cycle, the performance of the ECG monitoring network is analyzed. The results would be beneficial to the design and development of biomedical sensor networks using the IEEE 802.15.4 standard.

The organization of this paper is as follows. Section 2 introduces the IEEE 802.15.4 standard briefly. In Section 3, the performance analysis models, including transmission delay, end to end latency, and packet delivery rate are given. Then, the performance analysis of an ECG monitoring network is illustrated in Section 4. Finally, Section 5 gives the conclusion and future research discussions.

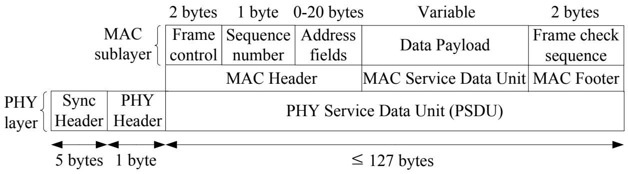

Figure 1. Data frame format of the IEEE 802.15.4

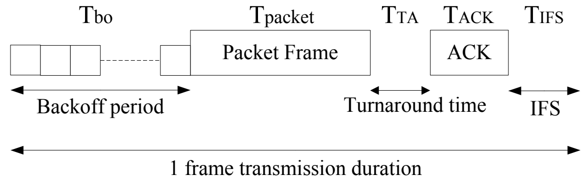

Figure 2. Frame transmission sequence of the IEEE 802.15.4

2. IEEE 802.15.4 Standard

The IEEE 802.15.4 standard defines the physical layer and the medium access control (MAC) sublayer. For the physical layer, three different frequency bands are available in the industrial scientific medical (ISM) band:

- 1 channel in the 868 MHz band with a raw data rate of 40 kbps (operate in Europe),
- 10 channels in the 915 MHz band each with a raw data rate of 40 kbps (operate in North America),
- 16 channels in the 2.4 GHz band each with a raw data rate of 250 kbps (worldwide available).

The IEEE 802.15.4 network supports two types of topologies, star topology and peer to peer topology. Four frame structures are defined in the IEEE 802.15.4 standard, including the beacon, MAC command, acknowledgment and data frames. The data frame is used for all transfers of data, the structure of data frame is shown in Fig. 1.

There are two operation modes in the IEEE 802.15.4 network, beacon enabled (slotted) and nonbeacon enabled (unslotted). In beacon enabled mode, communication is synchronized and controlled by a network coordinator, which transmits periodic beacons to define the start and the end of a superframe. The superframe may consist of active and inactive period, the active part of the superframe is divided into 16 equally sized slots and consists of 2 groups: the contention access period (CAP) and an optional contention free period (CFP). In the contention access period, slotted CSMA/CA is used as channel access mechanism, where the backoff slot aligns with the start of beacon transmission. In the contention free period, time slots are assigned by the coordinator, devices which have been assigned specific time slots can transmit packets in this period. All communications must take place during the active part. In the inactive part, devices can power down to conserve energy.

In nonbeacon enabled mode, no regular beacons are transmitted. Unslotted CSMA/CA is used as channel access mechanism. When a network device wishes to transmit packets to the network coordinator, it waits for a random number of backoff slots, which is chosen uniformly between 0 and $2^{BE}-1$, where BE is the backoff exponent. The default minimum value (macMinBE) is 3. It checks then if the channel is idle. If so, the network device begins to transmit data packet, if not, BE is incremented by 1, the network device backs off again with the new value of BE before trying to access the channel. The procedure is repeated until the number of BE exceeds the maximum number of backoff exponent (aMaxBE), which is 5. Similarly the number of iterations is also limited by NB, which stands for the maximum number of backoffs before declaring a channel access failure. The default value of NB is 4.

The data frame transmission sequence is shown in Fig. 2.

T_{bo} is the total backoff time, in other words, the amount of time of channel access delay. T_{packet} is transmission time for a data packet. T_{TA} is transceiver's transmitting to receiving turnaround time. T_{ACK} is transmission time for an ACK frame. T_{IFS} is time of Inter Frame Space (IFS). An IFS follows the transmitted frames to allow the MAC layer has enough time to process data received from the physical layer. The IFS could be SIFS or LIFS, depends on the size of the MAC frame.

A more detailed description of the IEEE 802.15.4 can be found in [4].

3. Performance Analysis

The performance of the IEEE 802.15.4 based biomedical sensor networks will be evaluated in terms of transmission delay, end to end latency, and packet delivery rate. The study will focus on single hop, star topology network.

3.1 Transmission Delay

We define packet transmission delay, T_l, is that the time needed to transmit a packet from the network device to the network coordinator, including the backoff time, packet transmission time, transceiver's transmitting to receiving turnaround time, ACK transmission time, and IFS time. From Fig. 2, the average transmission delay T_l can be calculated as [1].

$$T_l = T_{bo} + T_{packet} + T_{TA} + T_{ACK} + T_{IFS}. \tag{1}$$

T_{bo} is the sum of the average backoff time of each period. It may consist of several backoff periods (with limitation up to 5) and depends on both parameters of the network device and the wireless network traffic load.

With up to the number of b maximum backoff periods, the probability P_s that the device can successfully access the channel is given as [5].

$$P_s = \sum_{a=1}^{a=b} P_c(1-P_c)^{(a-1)}, \quad (2)$$

where P_c is the probability that a network device assesses the channel idle at the end of a backoff period. For a network consists of the number of n network devices, P_c is given as

$$P_c = (1-q)^{n-1}, \quad (3)$$

where q is the probability that a network device is transmitting at any given time.

The average number of backoff periods, R, is calculated as [5].

$$R = (1-P_s)b + \sum_{a=1}^{a=b} aP_c(1-P_c)^{(a-1)}. \quad (4)$$

Then the total backoff time, T_{bo}, can be calculated as:

$$T_{bo} = FractionalPart[R]T_{bop}(IntegerPart[R]+1) + \sum_{a=1}^{a=IntegerPart[R]} T_{bop}(a), \quad (5)$$

where $T_{bop}(a)$ is the average time of a backoff period, and given as

$$T_{bop}(a) = \frac{2^{macMinBE+a-1}-1}{2} T_{boslot}, \quad (6)$$

where $macMinBE$ is the initial value of BE and T_{boslot} is the duration of one backoff slot, which is equal to 20 symbol durations according to the IEEE 802.15.4 standard.

Packet transmission time, T_{packet}, is given as

$$T_{packet} = \frac{L_{PHY} + L_{MHR} + payload + L_{MFR}}{R_{data}}, \quad (7)$$

where L_{PHY} is the number of PHY header, L_{MHR} is the number of MAC header, *payload* is the number of data byte in the packet, L_{MFR} is the number of MAC footer, and R_{data} is the raw data transmission rate.

3.2 End to End Latency

For medical applications, the end to end latency is an important parameter. As part of an ECG system, a personal worn device (PWD) defined by the IEEE 1073 working group (i.e., a wireless electrode) generates 4 kbps of data and requires that the addition of the latency introduced by the packetization of the samples and transmission delay remain below 500 ms [6].

The output of biomedical sensor is usually analog signal, the network device digitizes and stores data in its buffer, and packetizes and transmits periodically. The sampling and transmitting cycle of a network device is shown in Fig. 3.

The end to end latency, T_e, is the amount of time between the packet begins to generate at the network device and the packet is received by the network coordinator. It is the sum of packet sampling time, T_{sam}, and packet transmission delay, T_l, as given by

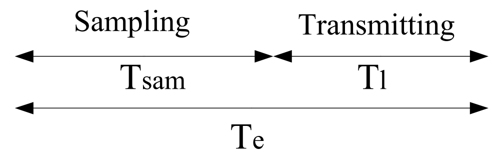

Figure 3. Sampling and transmitting cycle of a network device

$$T_e = T_{sam} + T_l. \quad (8)$$

The sampling time, T_{sam}, is the amount of time that the device samples the biomedical signal until the number of samples reaches a certain size.

3.3 Packet Delivery Rate

Even in perfect wireless channel conditions, packets may be lost due to two reasons. The first is channel access failure, the wireless channel becomes extremely busy when many network devices wish to transmit in a short period of time. If a network device cannot access the channel before the backoff exponent exceeds the maximum number of backoff exponent, channel access failure will be declared, and the packet will be discarded. The probability of successful channel access, P_s, is calculated in (2).

The second reason of packet loss is due to packet collision. Collision will occur when two or more nodes perform CCA and assess whether the channel idle at the same time, therefore two or more network devices will transmit simultaneously. If acknowledgment mechanism is not employed, the collided packet will not be retransmitted. The probability, P_{co}, that two network devices select the same backoff delay and collide can be modeled as

$$P_{co} = \frac{1}{2^{BE}-1}. \quad (9)$$

Considering the number of $n-1$ contending network devices, combining the channel access failure and packet collision probability, packet delivery rate, P_{der}, can be calculated as

$$P_{der} = \sum_{a=1}^{a=b} P_c(1-P_c)^{(a-1)}(1-P_{co})^m, \quad (10)$$

where m is given as

$$m = (n-1)q. \quad (11)$$

4. Case Study

In the case study, we consider a biomedical sensor network which is used to monitor patients' ECG signal. The ECG

Table 1. Parameters of network device

Parameters	Value
T_s	16 μs
T_{boslot}	320 μs
T_{TA}	192 μs
T_{SIFS}	192 μs
T_{LIFS}	640 μs
L_{PHY}	6 bytes
L_{MHR}	11 bytes
L_{MFR}	2 bytes
$macMinBE$	3
$aMaxBE$	5
$macCSMABackoffs$	4
Use of ACKs	No

signal is the electrical recording of the heart, which can be used by the cardiologist to diagnose heart diseases. The ECG monitoring network consists of one sink node and a number of n sensor nodes. The sink node works as a network coordinator, it collects ECG data packets transmitted from sensor nodes and forwards these packets to a medical server. The sensor nodes transmit the ECG data to the sink node. Both the sink node and the sensor nodes use the IEEE 802.15.4 compliant wireless transceivers, where 2.4 GHz band is used due to high raw data transmission rate and worldwide availability. The parameters of network devices used in the analysis are given in Table 1.

4.1 Network Topology

We consider a scenario where n sensor nodes are distributed circularly around a sink node. Single hop, star topology is used. The network is fully connected, where no hidden station problem exists. The study focuses on uplink communication, which means communication from the sensor nodes to the sink node. In order to achieve high network throughput and low latency, nonbeacon mode is employed due to less traffic transmission control overhead. 16 bit short addresses are used in the data packet.

4.2 Sampling and Transmitting Cycle of Sensor Node

An ECG biomedical sensor is connected to each sensor node's expansion IO port. The ECG sensor samples the heart activity signal, the sensor node digitizes and stores ECG data in its buffer, where the data will be packetized and transmitted when the number of data byte reaches a certain size. By varying the payload size and packet transmission rate, the performance of transmission delay, end to end latency and packet delivery rate are studied. Table 2 describes the sensor node's specifications. The sampling rate and resolution of ECG signal are referred to [7].

Table 2. Sensor node specifications

Transceiver's raw data rate	250 kbps
Biomedical sensor	ECG (3 leads)
Sampling rate	250 Hz
Sampling resolution	16 bits
ECG data rate	12 kbps

The sensor node samples the ECG signal, packetizes and transmits it periodically. The transmitting probability, q, can be approximately calculated as

$$q = \frac{T_r}{T_r + T_{sam}}, \tag{12}$$

where T_r and T_{sam} are packet transmission time and signal sampling time, respectively.

Then the probability of channel idle in a clear channel assessment (CCA) period can be calculated as

$$P_c = (1-q)^{(n-1)} = (\frac{T_{sam}}{T_r + T_{sam}})^{(n-1)}. \tag{13}$$

Considering the overhead of MAC sublayer and physical layer, packet transmission time, T_r, is calculated as

$$T_r = \frac{L_{PHY} + L_{MHR} + payload + L_{MFR}}{R_{data}}. \tag{14}$$

The signal sampling time is the number of payload in bits divided by the sampling rate, as given in

$$T_{sam} = \frac{payload}{Sampling\ rate}. \tag{15}$$

According to the IEEE 802.15.4 standard, the maximum size of MAC packet is 127 bytes. Thus the payload, i.e., the number of data byte that can be transmitted in one packet is limited. Using the parameters given in Table 1, where the total overhead of MAC packet is 13 bytes, therefore, the maximum payload size becomes 114 bytes.

4.3 Analysis Results

4.3.1 Transmission Delay

For non-ACKs mode, where the time of T_{ACK} and T_{TA} are 0, a $SIFS$ or $LIFS$ follows the transmitted data frame. The average transmission delay is illustrated in Fig. 4.

For a network consists of a certain number of sensor nodes, when the payload size increases, the transmission delay decreases till the payload size reach a certain number, then it begins to increase. The main reason is that both backoff delay and packet transmission time contribute to the transmission delay. When the payload size is small, the

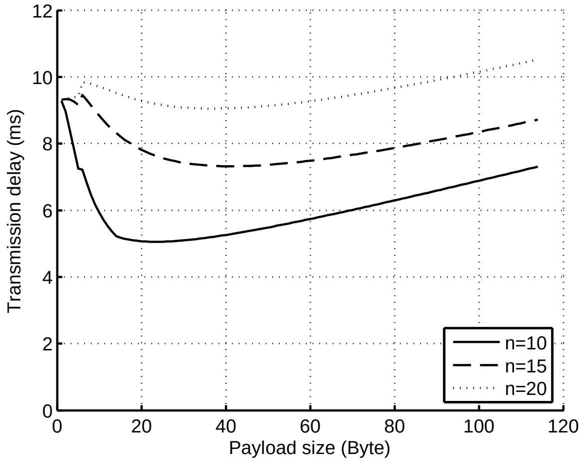

Figure 4. Effect of payload size on average transmission delay

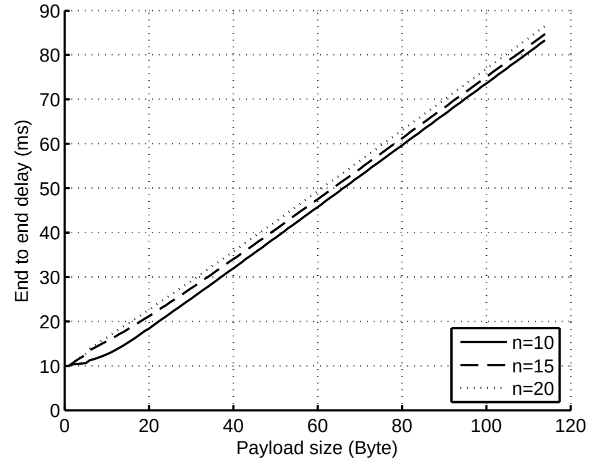

Figure 5. Effect of payload size on average end to end latency

main contribution of transmission delay is made by channel access delay. This is due to sensor nodes have to transmit small size data packet in a very short time interval, the channel becomes extremely busy. Subsequently, sensor nodes have to back off more periods to compete to access the channel. This will cause longer channel access delay. When the payload size grows over a certain number, the main contribution of the transmission delay is made by the packet transmission time. Large size packet needs more transmission time, hence, the transmission delay increases when the payload size grows.

It can be seen that for a given payload size, the transmission delay of a network with large number of sensor nodes is longer than a network with small number of sensor nodes. This could be explained in such a way that, in dense sensor networks, more sensor nodes compete to access the channel, thus nodes wish to transmit have to back off more periods to access the channel, which means longer channel access delay.

4.3.2 End to End Latency

The average end to end latency is the sum of transmission delay and signal sampling time, illustrated in Fig. 5.

Approximately, the end to end latency is a linear function of the payload size. The reason for this is that for a certain size data packet, the signal sampling time is much longer than the packet transmitting time. This means that the end to end latency is mainly caused by the signal sampling time, which is proportional to the payload size, as derived in (15).

The minimum end to end latency is about 10 ms with a minimum payload size, 1 byte. However, the packet delivery rate will be very low due to low channel efficiency and packet coding efficiency. For the largest payload size, 114 bytes, the end to end latency is about 90 ms, this complies with the requirements of wireless medical applications [6].

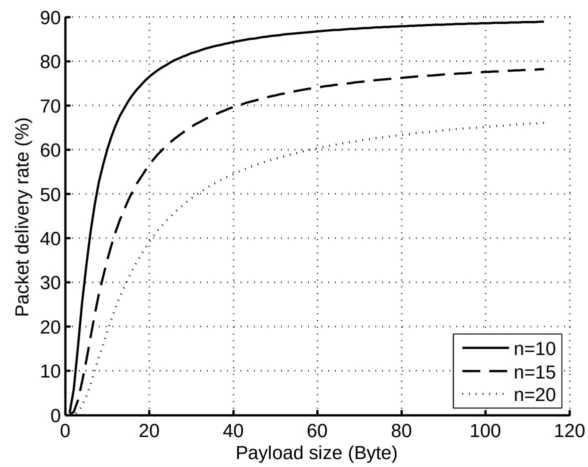

Figure 6. Effect of payload size on packet delivery rate

4.3.3 Packet Delivery Rate

The packet delivery rate is illustrated in Fig. 6.

For a network consists of a certain number of sensor nodes, the packet delivery rate increases when the payload size grows. This could be explained as the payload size increases, the sensor nodes try to transmit packets at longer time intervals, the probability of successful channel access becomes larger due to higher channel efficiency and packet coding efficiency.

We observed that for the same payload size, the packet delivery rate in denser network is lower. One reason may be that in denser sensor networks, more sensor nodes compete to access the channel, therefore the channel access failure probability becomes higher. The other reason can be that when the number of sensor nodes in a network grows, the probability that two or more sensor nodes simultaneously perform CCA and assess whether the channel idle increases, leading to larger probability of packet collision.

5. Conclusion

In this paper, we have investigated an IEEE 802.15.4 based ECG monitoring network, where transmission delay, end to end latency, and packet delivery rate were analyzed as performance metrics.

In the IEEE 802.15.4 standard based biomedical sensor network, both signal sampling time and transmission delay contribute to the end to end latency. But the end to end latency is mainly introduced by signal sampling time, especially for low data rate biomedical sensors. The packet delivery rate increases when the number of payload data becomes large due to high channel efficiency and packet coding efficiency. Subsequently, large size packet suffers high end to end latency. In the case study, for a full size MAC packet with maximum payload size (114 bytes), the average end to end latency introduced by sampling and transmitting is about 90 ms, and this still complies with the requirements of wireless medical applications. For time-critical applications, a payload size between 40 and 60 bytes can be selected due to lower end to end latency and acceptable packet delivery rate. In the design and development of biomedical sensor networks in time-critical medical care applications, trade-off between end to end latency and packet delivery rate must be considered.

In future research work, we will investigate the impacts of interferences from wireless local area network, Bluetooth and electrical noises caused by various medical devices in the hospital environments. We also intend to investigate biomedical sensor networks with dynamic topology, where the mobility of sensor nodes will be taken into account while the performance of biomedical sensor network is evaluated.

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