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A Low-Complexity Medium Access Control Framework for Body Sensor Networks

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Abstract—**This paper proposed a low-complexity medium access control (MAC) protocol tailored for body sensor networks (BSN) applications. The MAC protocol was designated to handle collision avoidance by reducing the numbers of the overhead packets for handshake control within the BSN. We also suggested a novel message recovery mechanism for getting back the lost physiological information. The adaptive synchronization scheme we have implemented exploited the features of multiple data-rate and adjustable precision design to support differentiated healthcare applications. The MAC protocol was fully implemented using our BSN development platform. The experimental results suggested the improved MAC design was compact and energy-efficient.**

I. Introduction

BODY sensor networks (BSN) is becoming a significant enabling technology for a wide variety of wearable applications. The motivation of having a BSN is to establish a pervasive healthcare system that is capable of monitoring human body's dynamic health conditions and transmitting the sensing data in a secure and real-time manner [1]. Typically, a BSN is equipped with different biosensors, such as a photoplethysmography (PPG) sensor, an electrocardiogram (ECG) sensor, a non-invasive blood pressure (NIBP) sensor, a blood oxygen saturation (SpO2) sensor and etc, for on-body / in-body physiological measurements. Consequently the data acquired from the multiple biosensor nodes is relayed wirelessly to the master node, also acted as a universal access point (UAP) device, such as a mobile phone or a PDA, where the data is processed autonomously [2].

In terms of the wireless communications the BSN has its unique characteristics that affect its efficiency in transmission delay, quality of service and power consumptions [3]. For example, replacing biosensors or charging batteries during the operation mode is unfavorable within the BSN and in some situations this even involves a surgery. Therefore the BSN must be energy-efficient. Besides, the BSN has relatively small scale structure with only 3-5 sensor nodes and works within body-proximal (typically less than 3 meters indoor); a star topology is preferred for BSN, wherein the master node with less resource constraints usually acts as the UAP between the BSN and outside network(s). In regards to the transmission delay the star network performs more efficient than a multi-hop network or an ad hoc deployment [4]. Finally, the time synchronization among BSN sensor nodes is usually critical. It is envisaged that the conventional wireless sensor network (WSN) protocols that are relatively bulky and power hungry are not suitable for BSN applications.

The most energy consuming component of the BSN nodes is wireless interface and its energy consumption mainly depends on the operations of Medium Access Control (MAC) [5]. Moreover, the MAC layer that stands between the physical link layer and upper layers handles the access to the communication channel and is vital for providing reliable links in MAC entities [6]. The MAC layer is relatively less proprietary and hardware-independent, makes it a good starting point for developing a customized BSN communication standard. In this paper, an ultra light-weight MAC protocol was proposed and the primary goal for the improved MAC design is to achieve low power and prolong operation life span. An IEEE 802.15.4 generic MAC protocol was referenced within our framework.

II. Related Works

There are a few researches dedicating to the development of various MAC algorithms. S-MAC [7], T-MAC [8] and DMAC [9] are typical contention-based MAC protocols in order to solve the idle listening problem by applying a synchronized duty cycle schedule between sensor nodes. However, these protocols are computationally complex and contain control package overheads that are redundant to star-topology based BSNs.

Design considerations linked to the BSN are usually low energy consumption, limited computational abilities, continuous operation and robustness. Reference [10] represented an H-MAC Time Division Multiple Access (TDMA) MAC protocol, aiming to improve BSN energy efficiency by exploiting heartbeat rhythm information to

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perform time synchronization. But this protocol is still premature, e.g. during the *in-situ* experiments the heartbeat rhythm was inevitably affected by noise.

The IEEE 802.15 Task Group 6 (Body Area Network) is developing a communication framework optimized for low power devices and operations on, in or around the human body to serve a variety of applications including medical, consumer electronics / personal entertainment and others [11]. Insofar the group has neither released any specific standards nor clarified the nominal frequency band(s).

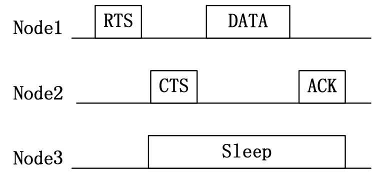
III. IMPROVED MAC PROTOCOL DESIGN

Our design was originated from the IEEE 802.15.4 generic MAC. Efforts were made towards the low energy consumption and improving the collision avoidance, message recovery and adaptive synchronization performances. Furthermore, our protocol was elaborated to facilitate the reusability of the source code and minimize the overhead of the program binary.

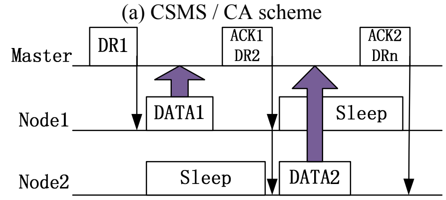
A. Collision Avoidance

In a star-topology multiple sensor nodes might send data to the master node simultaneously or within very short time interval, therefore collision avoidance is of vital importance. However, the conventional Carrier Sense Multiple Access / Collision Avoidance (CSMA / CA) mechanism using RTS / CTS / DATA / ACK between the sender and the receiver [12] is relatively ‘overweighed’ when deployed in the single-master-centralized BSN, for example, the complex control overhead inevitably deteriorates the network latency. Therefore we presented a DR & ACK / DATA mechanism to simplify this situation.

The major change against the former art is that our protocol was designed to be asymmetrical, i.e. much of the network and protocol complexity was allocated in the master node, rather than distributed evenly among the power-constrained biosensor nodes. Fig. 1(a) shows a conventional Collision Avoidance method applied for multi-hop distributed computing. Fig. 1(b) depicts our approach. In Fig. 1(b), suppose all nodes are time synchronized, the Master sends out a Data Request (DR) message, subsequently other nodes hear the transmission of the DR. If the Node1 finds that the DR message is calling the address of its own, then the Node1 sends DATA to the Master, meantime other nodes should sleep until the current transmission is over. Once the Master has received DATA1 beacon from Node1, it responds with an ACK1 & DR2 beacon. This time the ACK1 message denotes the acknowledgement of the Master, and DR2 shows the Data Request message towards Node2. In this design the ACK_X and DR_{X+1} beacons were combined together as one beacon for energy saving.



(a) CSMS / CA scheme



(b) DR & ACK / DATA scheme

Fig. 1. Collision avoidance illustrations.

Since BSN nodes work within a short range, wireless link is relatively reliable and Error Packet Rate (EPR) is relatively low (less than 0.1% as tested in our previous experiments [13]), in this case the DR & ACK / DATA scheme works effectively. However, if the wireless link becomes deteriorated and EPR raises, the DATA packets may lose. To maintain the data integrality within the BSN we introduced a message recovery scheme when the master loses data information.

B. Message Recovery

Within a BSN message loss could happen due to various situations. There are two types of message loss, ACK loss (also includes DATA loss) and DR loss. DR loss can be recovered by DR beacon retransmission when the channel is not occupied. When there is an ACK loss, the certain sensor node reserves the current DATA packet in its memory, and then, the new sampling DATA is shifted to the back of the former DATA. While the next DR beacon comes, this sensor node sends out a 1-plus time slot request along with the DATA message for one more DR schedule from the Master. After that the Master rearranges the time schedule so that the lost message can be retransmitted in the next DATA transmission pipeline. The recovery solution is depicted in Fig. 2.

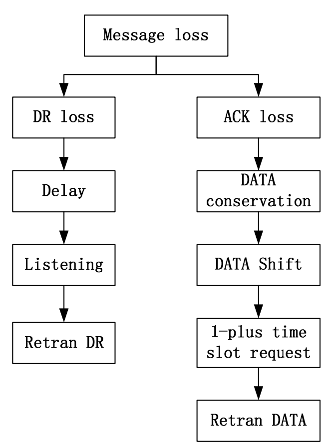


Fig. 2. The message recovery solution.

Finally, retransmissions were only allowed up to a certain limit at which the current packet should be ignored, this way the issues that lead to undesirable energy wastage were avoided.

C. Adaptive Synchronization Scheme

Time synchronization is crucial in providing a sustainable network communication [14]. Even if all the sensor nodes could precisely agree on the start of a health monitoring session, a running local time would only work for short session durations. Besides, each sensor node in the BSN has a local clock source with an associated skew [15]. In this session we introduced a synchronization scheme that adaptively adjusts the synchronization interval. This scheme attempts to put forward an adaptive way to accurately capture the unusual abnormalities.

The basic scheme was shown in Fig. 3. The master node was used as the local time reference. The sensor node sends out a Data Variation Ratio (DVR) that was calculated by the acquired data along with the DATA beacon. Once the master node received the DVR message, it compares the DVR with its threshold value. Consequently a SYNC interval that is used for time synchronization was counted up. After this procedure, the time slots should be reassigned for data request. Finally, the master node transmits the SYNC packet along with the DR beacon that is filled with the reference clock information. Sensor node(s) adjusts its timer(s) immediately after the SYNC packet was received. For *in-situ* dynamic monitoring of physiological parameters the adaptive scheme is beneficial for identifying transient but life threatening events.

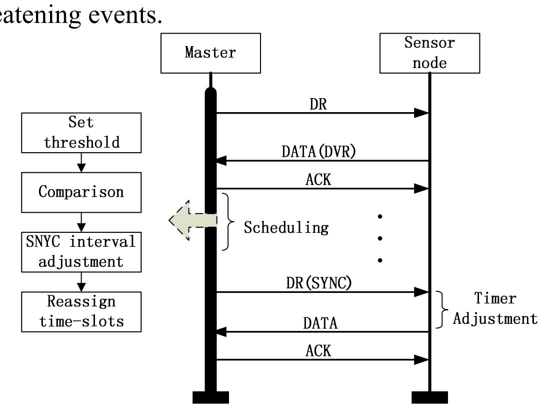


Fig. 3. Adaptive synchronization scheme.

IV. PROTOCOL IMPLEMENTATION

The purpose of the implementation is to demonstrate the performance of the low-complexity MAC protocol for BSN applications.

A. Implementation Platform

A BSN development platform (Fig. 4) was used to verify our protocol. Each BSN node equipped with an ultra-low-power microprocessor (MSP430 from TI) and a low-power GFSK-modulated radio transceiver (nRF905 from Nordic). The transmission rate could be up to 50 Kbps [13].

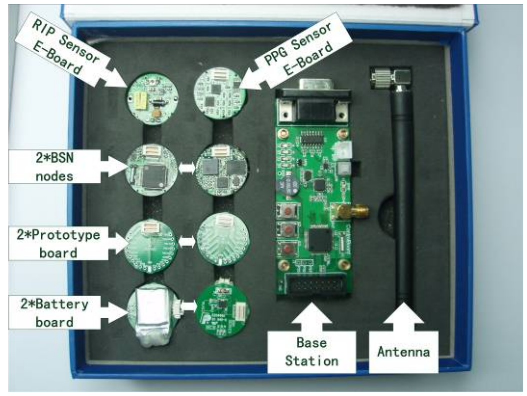


Fig. 4. BSN development platform. The platform includes a PPG sensor electronics board, a respiratory inductive plethysmograph sensor (RIP) electronics board, two BSN node boards, two prototyping boards, two battery boards, a base station board and a whip antenna. All the boards, except the base station board were designed in a uniform form factor that is 23 millimeters in diameter.

The MAC protocol we have developed was fully implemented into the BSN node. The assembled codes only occupied 1.6 Kbytes program memory space. The compact and low-complexity nature of our protocol makes it suitable for further exploitations of BSN network architecture and inter-connectivity. The protocol was programmed using C so it is easy to be implemented into other hardware platforms.

To evaluate the performances of the MAC protocol, a body sensor network was formed using the development platform. The base station board acted as the master node and up to six BSN node boards connected with different biosensors acted as the sensor nodes. During experiments all the boards were deployed around body proximal within the short communication range of less than 3 meters. The whip antenna was connected with the base station board.

B. Power Consumption Comparison

The averaging power consumption of the BSN node was measured in different transmission intervals, as illustrated in Fig. 5. We compared the power consumptions of transmitting 32 payloads at a time in one period, either using our scheme or the conventional RTS / CTS / DATA / ACK handshake protocol. It was clearly indicated that our scheme outperformed the conventional protocol in terms of the energy efficiency. The power savings were more significant when shorter data transmission intervals were set.

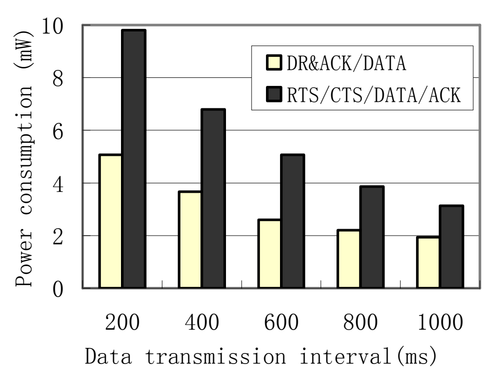


Fig. 5. Power consumptions at different data transmission intervals.

C. *Throughput test*

Network throughput was measured at different SYNC beacon intervals. We tested the throughput by counting up the transmission data via a serial-port debug assistant terminal. It was indicated in Fig. 6 that the network throughput was decreased when the synchronization interval increased. When the synchronization interval was relatively longer (i.e. more than 10 seconds), there was no significant difference in terms of network throughput no matter how many retransmissions were attempted.

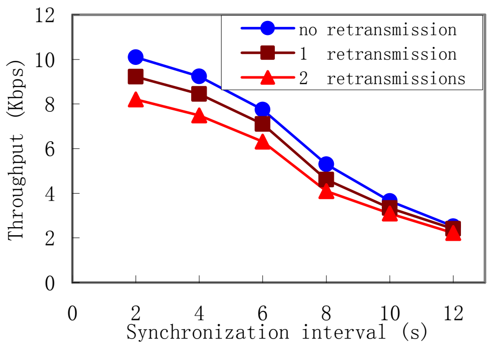


Fig. 6. Throughput with different SYNC intervals when the numbers of the message retransmission varied from 0 to 2.

D. *Energy Cost Measurement*

The energy cost was measured at different data size, as illustrated in Fig. 7. Each BSN node synchronizes with the base station at a fixed 5 s interval or 10 s interval. The data transmission interval was set to be 1 s. It was indicated that the energy cost was approximately 6 J/Mb with our MAC protocol and BSN node. The S-MAC [7] was tentatively implemented with our BSN node. Results indicated that the energy cost figure was approximately 20 J/Mb and its network latency was poorer.

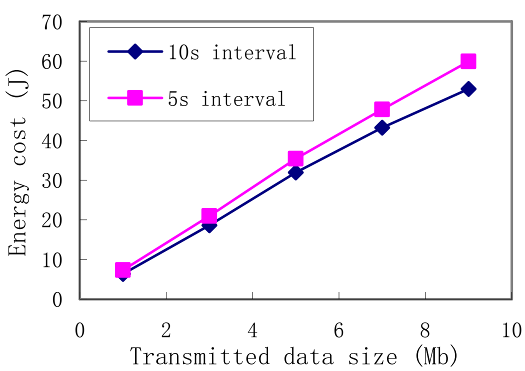


Fig. 7. Energy cost at different transmitted data size.

V. CONCLUSION

Body sensor networks have different requirements in terms of communication energy, throughput and resilience to packet-losses. In this paper we presented a low-complexity MAC protocol rooted from the IEEE 802.15.4 generic MAC but specially tailored for BSN applications. Our protocol was consisted of a simplified collision avoidance scheme aiming at reducing unnecessary control packet overheads by pipeline forwarding. An efficient retransmission mechanism was included to recovery the lost messages. The protocol was successfully implemented into our BSN development platform. The results concluded that our implementation was effective and energy-efficient. In the future we will testify the MAC protocol using various *in-situ* experiments, and also the QoS of our applications will be presented.

REFERENCES

[1] G.Z. Yang, *Body Sensor Networks*. Springer-Verlag London, 2006.

[2] A. Natarajan, M. Motani, B. De Silva, K.K. Yap, and K.C. Chua. "Investigating network architectures for body sensor networks," International Conf. on Mobile Systems, 2007, pp. 19-24.

[3] Okundu Omeni, Alan Chi Wai Wong Alison J. Burdett, Christofer Toumazou, "Energy efficient medium access protocol for wireless medical body area sensor networks," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 2, no. 4, 2008, pp. 251-259.

[4] Huaming Li, Jindong Tan, "An ultra-low-power medium access control protocol for body sensor network," 27th Annual International Conference of the Engineering in Medical and Biology Society, IEEE-EMBS, 2005, pp. 2451-2454.

[5] Jaesub Kim, Keuntae Park, Daeyeon Park, "An energy-efficient scheduling MAC protocol for wireless sensor networks," CCNC 2007, 2007, pp. 655-659.

[6] I.E. Lamprinos, A. Prentza, E. Sakka, and D. Koutsouris, "Energy-efficient MAC protocol for patient personal area networks," IEEE Eng. Med. Biology Soc., 2005, pp. 3799-3802.

[7] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in Proc. IEEE 21st Ann. Joint Conf. IEEE Comput. Commun. Soc., 2002, vol. 3, pp. 1567-1576.

[8] T. van Dam, K. Langendoen, "An adaptive energy efficient MAC protocol for wireless sensor networks," 1st ACM Conf. on Embedded Networked Sensor Systems (Sen-Sys 2003), 2003, pp. 171-180.

[9] Rajgopal Kannan, Ram Kalidindi, S. S. Lyengar, Vijay Kumar, "Energy and rate based MAC protocol for wireless sensor networks," SIGMOD Rec. 32, 4, 2003, pp. 60-65.

[10] Huaming Li, Jindong Tan, "Medium access control for body sensor networks," Computer Communications and Networks, ICCCN2007, pp. 210-215.

[11] Jan Magne Tjensvold, Comparison of the IEEE 802.11, 802.15.1, 802.15.4 and 802.15.6 wireless standards, 2007.

[12] Sun Li-ming, Chen Yu, Zhu Hong-song, *Wireless Sensor Networks*, Tsinghua University Press, Beijing, 2005.

[13] B. Wang, L. Wang, B.Y. Huang, S.J. Lin, D. Wu, Y.T. Zhang, Q. Yin, and W. Chen, "A body sensor networks development platform for pervasive healthcare," The 3rd International Conference on Bioinformatics and Biomedical Engineering, Beijing, 2009, to be published.

[14] Edgar H. Callaway, *Wireless Sensor Networks: Architectures and Protocols*, CRC Press, Boca Raton, 2004.

[15] C. Otto, A. Milenkovic, C. Sanders, E. Jovanov, "System architecture of a wireless body area sensor network for ubiquitous health monitoring," *Journal of Mobile Multimedia*, vol. 1, no. 4, 2006, pp. 307-326.