POWER SAVING ORIENTED MEDIUM ACCESS CONTROL PROTOCOL FOR PATIENT PERSONAL AREA NETWORKS

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Abstract: Continuous, remote monitoring of crucial vital signs of patients with the use of medical sensors is a key demand in modern healthcare provision. By networking various medical sensors and a supervising node wirelessly, we build a patient Personal Area Network (pPAN), whose infrastructure extends the environment of healthcare provision out of hospital. Given that one of the most critical parameters for the success of a pPAN application is its energy efficiency, the Medium Access Control (MAC) protocol, which manages the physical link and organizes the interoperation of the nodes of the network, should be definitely oriented towards the satisfaction of the power conservation factor. Towards this direction we propose the pPAN-MAC protocol, which aims at the optimization of specific MAC design parameters, to ensure proper communication between the nodes of a medical sensor network, while ensuring energy efficient operation.

Introduction

When considering the modern trends in healthcare provision, pPANs hold significant importance [1], [2]. It concerns a (wireless) infrastructure, consisting of several medical sensors and a supervising device, placed in relatively short distance between them, which provides the capability for continuous monitoring of patient's health condition and control of several operations, through data exchange between the sensors and the administrating node.

For sound and efficient data exchange in pPANs, an application specific MAC protocol is necessary. Its major purpose is to ensure efficient usage of the physical communication channel by the nodes of the network, while providing error free data transfer to the network layer above it. Especially when considering a MAC protocol for wireless medical sensor network, energy management plays very important role.

The sharing of a single communication channel by multiple nodes inducts the phenomenon of packet collision. The simultaneous transmission from more than one node of a pPAN and the consecutive retransmission demand, increases the overall traffic and the overhead in the communication channel, reduces the throughput of the system and, finally, it results in undesirable energy wastage. Thus, an appropriate policy to ensure the greatest possible avoidance of this deficiency is required.

Another issue to examine when considering a power saving oriented MAC protocol design is how to eliminate idle listening periods, during which a node is listening to the communication channel without actually receiving data. In the majority of traditional MAC protocols the nodes are not aware of the instance they will be addressed by another member of the network. This feature raises the demand for relatively extended operation in receiving mode, particularly when the elimination of retransmissions and data loss is highly prioritized. Especially in wireless medical sensor networks, the requirement for idle listening elimination is favoured by the fact that the frequency in which data exchange between the nodes occurs does not justify the receiver to be continuously switched on. With a clever system design, the amount of energy being spent on monitoring the channel can be minimized.

In the context described above, we present in this paper the pPAN-MAC protocol, which aims at taking into consideration the unique features and demands of the nodes comprising a pPAN, in order to ensure proper communication between them, while giving high priority to power saving operation.

Materials and Methods

Hardware infrastructure

The design of the proposed MAC protocol is based among others on some basic features of the hardware components we use in our prototype. The transceiver (Nordic nRF2401, [3]) operates in the licence free 2.4 - 2.5 GHz ISM band and can achieve transmission rates of up to 1 Mbps. Although it can support frequency hopping and multi channel operation, in the context of this paper we examine the pPAN-MAC version for single channel operation. The transmission power and reception sensitivity can be selected by software, enabling the possibility of building in software a method for power control, which is part of the pPAN-MAC protocol functionality. The transceiver is externally controlled by an ultra low power, 16-bit microcontroller (Texas Instruments MSP430F149, [4]), whose available memory defines the maximum length of data queue to

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be transmitted, in the absence of external buffers.

pPAN-MAC functionality

The pPAN-MAC protocol is designed to support star topology. This means that the network consists of a master, the administrating node, and several slaves, the medical sensor nodes and that the typical communication paths link only master with slaves and not slave with slave. Two reasons support this choice:

- The first is that the nature of information exchanged in pPANs does not necessitate for establishment of communication paths among all pairs of nodes. Only the supervising node is interested on the information recorded by the sensor nodes and, additionally, it is the only one responsible to initialize, maintain and control their operation.
- The second reason is that there would be no need to support communication between sensors, unless in order to retrieve an efficient communication path between remote sensors and the administrating node. Such a demand would require appropriate routing algorithms. In most pPAN applications, however, the network consists of a rather limited number of sensors which are placed in relatively short distance among them and thus they face almost the same signal propagation conditions. Running routing algorithms for such an application would rather overkill the processing and energy resources of the sensor nodes and thus is kept off our approach.

Under this context it would be redundant to build a MAC protocol for peer to peer communication, given that this would increase its complexity, the traffic in the communication channel and the overall processing demands, resulting in energy outspending. Nevertheless, the pPAN-MAC protocol supports broadcast transmission, as a mean for informing simultaneously all the nodes about channel access issues, as we will see later.

The pPAN-MAC protocol uses the principal of slotted timeline to differentiate the operation mode of the transceiver of the nodes and allow only specific processes to take place during each period. More specifically, four types of timeslots are defined:

- Transmission Slot (TX Slot); only during such a timeslot a transmission can take place.
- Reception Slot (RX Slot); during this timeslot a node can set its transceiver in receiving mode to listen to the communication channel.
- Stand By Slot (SB Slot); the transceiver of the node is set to power saving stand by mode.
- Receive to Synchronize Slot (RXS Slot); it appears in slave's timeslot alteration only and concerns an RX type slot which endures longer in order to make feasible the synchronization of the slave with the master node.

The duration of the first three types of timeslots equals to *T*. The RXS slot lasts *3T*. This value ensures that, whenever a slave node needs to get synchronized with the master node and switches on to RXS-SB slot alteration, it will be definitely operating in receiving mode until at least the next TX slot of the master (figure 1).

Additionally to the duration, the alteration schema of the timeslots is predefined and based on the idea that in order to ensure proper communication between the slaves and the master, the former should transmit only whenever the latter operates in receiving mode and vice versa (figure 2).

The need for synchronization of the slaves with the master node imposes significant timing requirements, concerning their operation. During the setup of the network the slave nodes alternate between SB and RXS slots. When a node tracks down a packet designated for it, it calculates an offset time:

$$OT = T - \frac{PL}{BP} \qquad (1)$$

combining the predefined duration of normal timeslots *T*, the length of the received packet *PL* (number of bits) and the transmission bit rate *BR*, in order to adapt its transition from RXS Slot to TX Slot to the master's transition from TX Slot to RX Slot (figure 1).

For a thoroughly estimation of the OT the equation should also include propagation delay and the turnaround for alteration of operation mode in the transceiver. The former is negligible when considering pPAN applications and the latter is estimated to be less than a few hundreds microseconds for the transceiver of our prototype and for this reason we make do with the above formula.

The pPAN-MAC protocol handles two types of packets. The first is derived when the next higher communication layer has payload to send and is called

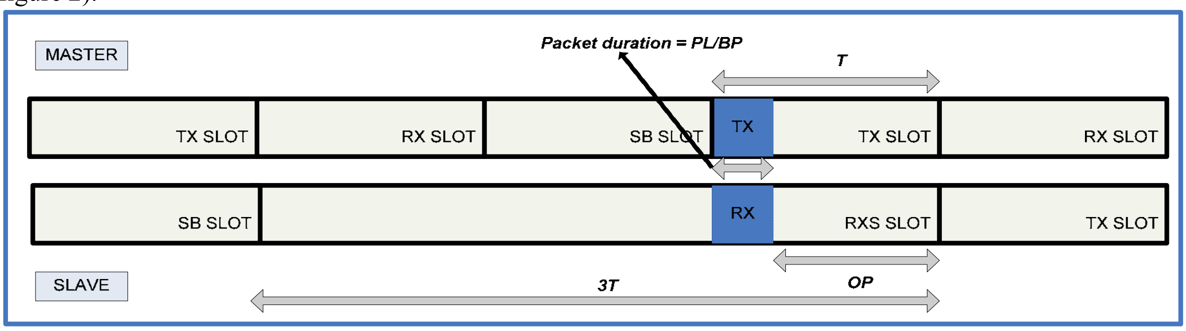

Figure 1: Synchronization procedure

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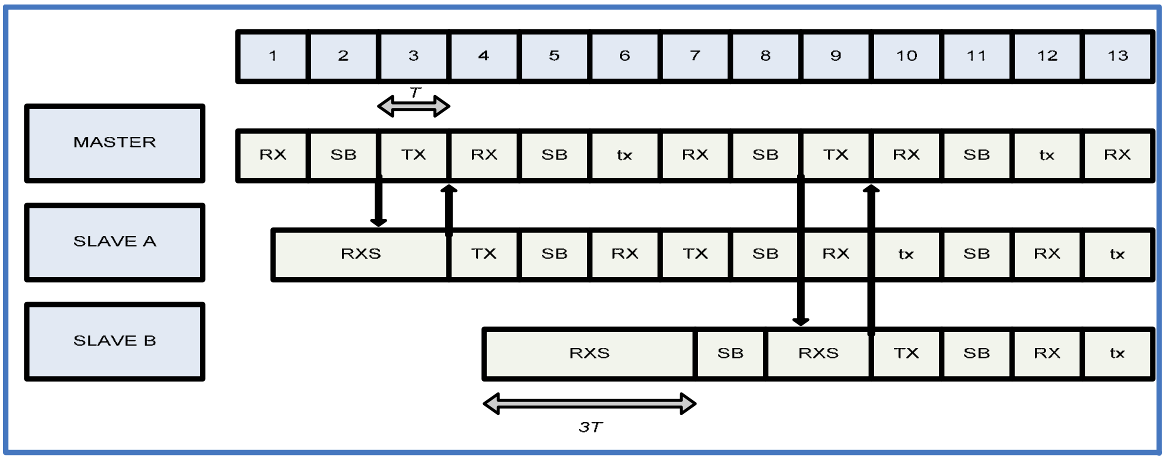

Figure 2: Timeslot alteration for master and slave nodes.

data packet. Apart from the payload, these packets include header with MAC related control fields and footer with a CRC field. These attachments to the payload are used by the pPAN-MAC software for communication management and integrity check, respectively. The second type of packet is the control packet, which is derived internally from MAC layer processes in order to ensure proper usage of the communication channel. In the context of the pPAN-MAC protocol we define the following control packets:

- Token Request packet
- Token Grant packet
- Polling Request packet
- Polling Response packet
- Node Initialization packet
- Node statistics Request
- Node statistics Response
- Acknowledgement packet

The access of the slave nodes to the communication channel is based on a variant of the Request to Send – Clear to Send (RTS-CTS) scheme used in several MAC protocols ([5], [6]). The basic idea remains the same; a slave node acquires access to the communication channel only when the master node grants it the right to do so. In order, however, to eliminate the overhead caused by the RTS-CTS packet exchange and adjust the channel sharing to the different traffic demands imposed by medical sensors (e.g. an ECG sensor potentially produces higher data traffic than a temperature sensor) we define the Token Request and Token Grant packets (respectively to RTS-CTS packets), which carry information about the demanded by the sensor duration of the right to transmit and the final assignment by the master node, respectively. The maximum token duration is set to K TX slots.

The Token Grant packet is broadcasted to all the sensor nodes. By this way all the members of the pPAN are aware of the grant and do not attempt to acquire access to the channel for the duration of the token. Upon the expiration of a token each slave node, except for the previous holder of the token, has the right to compete for acquiring access to the communication channel. The blockade of the previously transmitting slave endures one TX slot and should be interpreted as an action of fairly and efficiently assigning the channel to the slaves of the network.

The proper reception of a data packet by a node must be followed by an acknowledgement response. For a control packet reception this response may be either a coupling control packet, whenever applicable (i.e. polling request–polling response) or the general purpose Acknowledgement control packet. In the lack of sound and timely response the transmitting node has the right to retransmit the packet, unless it has reached the maximum number of retransmissions R, or its token has expired.

The proposed pPAN-MAC protocol also supports joint transmission of control and data packets, whenever applicable, conducing in deduction of the overhead in the communication channel. This means that whenever a node has data and control packets intended to the same destination, it transmits both of them in a single packet. Additionally, if an Acknowledgement or control packet response is pending and a data packet for the same destination is queued, joint transmission is executed, even in the lack of token, accelerating the overall communication.

The master node maintains a table with information considering its contacts with the slave nodes. Protracted absence of communication with a specific node triggers the transmission of a Polling Request packet. This is useful not only for the master, in order to check the integrity of the pPAN, but also for the slaves, in order to keep synchronized with the master.

Finally, the pPAN-MAC protocol supports the processing of link statistics (i.e. corrected bits, erroneous packets, number of retransmissions) and exchange of the derived information with the use of the Node statistics Request/Response packets. This feature is exploited in the integration of a management process for transmission power and reception sensitivity level and conduces in improvement of power consumption.

Collision avoidance

The avoidance of packet collisions due to contemporaneous transmission from more than one

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node of the network plays significant role in building a power saving oriented MAC protocol and is one of the major issues the pPAN-MAC protocol deals with. Our approach concerning this subject begins with two major hypotheses:

- Only a single channel is available to be shared by multiple nodes and thus the pPAN-MAC protocol should include a policy for rational management of this resource.
- Since the nodes of the pPAN are relatively close together, being attached to patient's body, the resulting topology allows us to omit, at least in the first approach of pPAN-MAC design, the problem of hidden terminal [7] which aggravates several ad hoc networks.

In the context described above, the pPAN-MAC protocol practices collision avoidance firstly by exploiting the slotted timeline. The different timeslot alteration schemes of the master and slave nodes (figure 2) ensure that as far as the nodes remain synchronized, there is no possibility of collision between the master and a slave node transmission, since their TX slots do not overlap.

Next demand to be met is the avoidance of collision between contemporaneous slaves' transmissions. At a first glance the proposed timeslot alteration renders rather possible such a phenomenon and thus, additional preventive measures are necessary. A solution towards this direction is the use of token for access to the communication channel. According to the pPAN-MAC protocol, whenever a slave node has data to transmit, first it contents to acquire the authority to do so, by the master node. This is carried out through the exchange of Token Request – Token Grant control packets, described above. This approach makes practically impossible the collision between two data packets and bounds the problem in the contemporaneous transmission of Token Request control packets.

An interesting issue that rises at this point is that, as pPAN-MAC is a contention based protocol, the contention schema affects its efficiency, since it is normally the only reason for packet collision. The nodes do not execute carrier sensing, and thus they get aware of a collision, only after not receiving a response during their very next RX slot. In order to restrain the nodes from sequential unsuccessful -due to collision- attempts to acquire the token, the pPAN-MAC protocol introduces weight factors for the queued packets. After a Token Request packet collision, the selection of the next TX slot during which a sensor will attempt to acquire the right to transmit is based on the following criteria, with declining weight factor:

- The node has a high priority data packet to transmit (e.g. it conveys an alarm indication).
- The node has a normal data packet to transmit (it conveys regular data e.g. periodical measurements).
- The node has a control packet to transmit (Acknowledgements are excluded from this scaling, since no token is necessary to acknowledge a packet reception).

In the first case, the node, instead of insisting on acquiring the token, it proceeds with transmitting the alarming data packet, until successive reception by the master node. In the other two cases it backs off for a number of timeslots, which is conversely proportional to the weight factor of the packet and the number of timeslots since its last token possession.

The aforementioned approach de-correlates significantly the token request schemas of the sensors and diminishes the possibility of sequential packet collisions.

Idle listening elimination

The consideration of idle listening problem holds special importance in medical sensor networks since the available energy resources are limited. The enhancement of the pPAN-MAC protocol with idle listening elimination features is favoured by the fact that the purpose for which the pPANs are built makes data traffic rather sporadic –such networks are not intended to continuously transmit raw data. Additionally, the communication link between the sensors and the supervising node is rather asymmetric, with most traffic flowing uplink, from the slaves to the master. What pPANs are usually expected to support are a periodic transmission of recorded data and an exceptional transmission of alarm indications. Thus, the communication channel is expected to be idle for long, but not predefined and predictable periods.

Based on these assumptions, the pPAN-MAC protocol embodies the definition of the SB slot and allows transceivers to switch to power saving stand by mode for at least 1/3 of period. This implementation results in an initial reduction in duty cycle by 33% and a consequent 33% reduction in energy consumption. Moreover, the aforementioned synchronization of the alteration of timeslots between the slaves and the master of the network allows further limitation of overhearing; in the dawn of RX slots, each node executes packet sensing -contrarily to carrier sensing, which is carried out by the physical layer, packet sensing is responsibility of the pPAN-MAC software, which decodes and analyzes the incoming bit stream- and if it does not track down successively its address -conveyed in the header of the packet- or the packet is not of broadcast type, it switches directly to stand by mode. In such cases the transceiver operates in stand by mode for almost the entirety of the RX slot, reducing drastically its idle listening to the communication channel.

The described policy causes that the nodes keep their receiver open for the shortest possible time, resulting in significant cut down in the duty cycle and power consumption. It should also be stated that the timeslot alteration scheme does not result in severe deterioration of transmission delay, since the waiting time for a slave node that has a packet ready to transmit and is the holder of the token cannot be greater than the duration of two timeslots.

Discussion

In this paper, we presented the main features of the pPAN-MAC protocol, which aims to improve energy efficiency in wireless medical sensor network applications, by giving emphasis in the prevention of two key energy wastage sources, the collision of packets due to transmissions overlapping and the communication channel overhearing.

The proposed pPAN-MAC protocol forces the nodes to have their receiver open for the shortest possible time, resulting in significant cut down in duty cycle and power consumption. To crystallize this we refer that, for the transceiver of our prototype, the operation in receiving mode is almost 1000 times greater than in stand by mode, which clearly shows the importance of idle listening avoidance.

Finally the pPAN-MAC protocol places great emphasis to the formulation of a context for noteworthy avoidance of packet collisions, although this has an impact to the data transmission delay.

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