Review Article

A Review of Energy Efficiency in Wireless Body Area/Sensor Networks, With Emphasis on MAC Protocol

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Abstract: The increasing use of wireless communication and the continuous miniaturisation of electronics devices have brought about the concept of Wireless Body Area Network (WBANs). In these types of networks, the sensor node operates in close proximity to the body and also the wireless nature of the system presents various novel, real-time and new methods to improve health care delivery. The sensor is capable of measuring any parameter which it has been designed to read, for example the heartrate and the body temperature. This paper presents a review of the concept of WBANs with a focus on the mechanism of data communication over the wireless medium. Further, it examines ways to power such devices, in particular focusing on minimisation of energy requirements, thereby reducing maintenance demands and contributing to making the environment 'greener'.

Keywords: ***Energy efficiency; Healthcare delivery; MAC protocol; Sensor networks; Wireless body area network***

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1. Introduction

In wireless body sensor network research, energy saving approaches have attracted attention since the sensor nodes must operate with a restricted energy supply from a very small source such as a miniature battery or an energy-harvesting system. The low energy usage requirement comes from the attributes of typical target systems based on the positioning of nodes that can be implanted or placed on the body and are expected to operate for very long periods of time (though not endlessly) on a single battery, or utilise energy harvested from its surroundings.

The radio components of a regular WSN node have been identified to use most of the energy in the system as the sensed data must be transmitted via the wireless medium. Hence, the greatest part of energy efficiency research has focused on communication protocols which save energy. The communication between nodes has made the Medium Access Control (MAC) protocol the main target of finding the most appropriate adaptive approach of communication between these nodes while minimising network resources.

The diagram in Fig. 1 shows a comprehensive system model, linked with the MAC protocol which is responsible for data communication. It comprises a free ambient energy source, the harvesting subsystem and the storage or backup system for holding the excess energy harvested and supplying the ambient energy to the sensor node.

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2. Medium Access Control (MAC) Protocol

The radio frequency spectrum is shared into frequency bands assigned to networking devices. The implementation of these frequencies can be achieved using frequency division multiple access (FDMA), time spread spectrum methods similar to Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA) and frequency skipping [1]. Due to the fading of power of signals with distance, it may be possible to reuse similar resources at two sites as long as they are at adequate distance from each other.

The communication channel distribution used in transmitting systems can be static or active. In static mode, channel resources are allocated permanently to a specific link. In a device where many computing systems are inter-linked via wireless, it is impractical to share a channel to each system. One responsibility of the MAC protocol as a sub-layer of the data link of the Open System Interconnection (OSI) model is to determine the limits or boundaries of frames and the recognition and arbitration of access to a channel shared by all nodes in the network [2]. The MAC protocol can be grouped according to various features. The most basic protocols found in WSNs can be grouped based on the status of the management into centralised, distributed, contention-free, contention-based or hybrid [3].

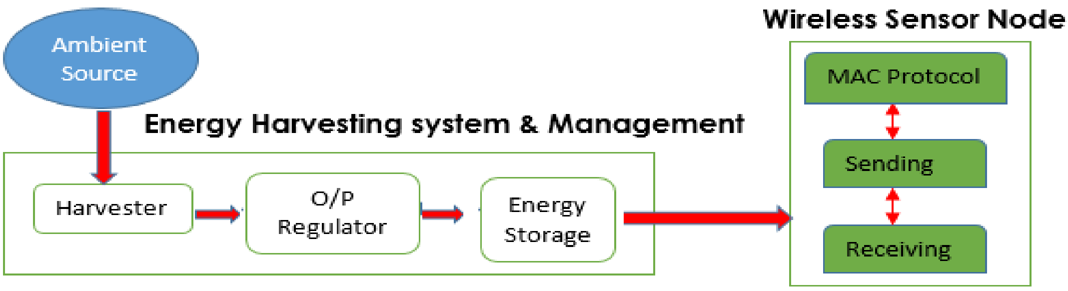

Figure 1. Architecture of typical energy harvesting system powering a sensor node

For a centralised MAC protocol, a core controller is responsible for controlling the medium. Centralisation makes it easy to control algorithms and designs but needs a star topology and often adds more computing demand and additional power utilisation on the core controller: an example of this protocol is seen in mobile networks. In contrast, in a distributed MAC protocol all nodes run the same rules in the network, because they do not depend on the core control from a main station; hence, they may well be appropriate for multi-hop communication. Cluster core control techniques are found in multi-hop networks, substituting the responsibility of the core controller in nearby nodes, so as to distribute the extra power utilised by the core controller within all sensor nodes.

3. Sources of Energy Waste in MAC

A number of sources contribute to energy waste, including data collisions, overhearing, idle listening, control packet overhead and traffic instabilities [1]. The major contributor to energy wastage is collision, which arises when two or more nodes attempt to send packets at the same time. Idle listening arises when a sensor node unnecessarily listens to an idle medium to receive likely packets or traffic. Overhearing occurs when a node receives a packet destined for other nodes. Nevertheless, when the traffic load is controlled centrally, idle listening and overhearing may be unnoticed.

Bursty traffic periods will arise in several applications and to send traffic at this time with reduced collisions, the system must be designed with caution to avoid jamming. Besides, in WBAN or small WSNs, idle listening, overhearing and collision may be decreased by employing master-slave architecture with TDMA/ Clear Channel Assessment (CCA) [1]. This technique minimises the possibility of collisions and idle listening leading to substantial energy saving.

4. Energy Reduction Procedures in MAC Protocol

Energy efficiency is a crucial issue due to the restricted energy of the sensor nodes and the longer period of system operation anticipated. One goal of saving this energy wastage in MAC is to improve the network lifespan and boost MAC protocol implementation. In achieving this, different wake-up approaches including asynchronous; Low Power Listening (LPL) or Synchronous (SYNC), Schedule Contention or TDMA were considered.

For the Low Power Listening technique, a node wakes up for a very short period to scan for channel traffics. This protocol employs channel polling to check whether a node needs to stay awake for data transfer: as a result, this decreases the activity of idle listening [3] but when the channel is silent, nodes may enter sleep state or they may stay active to receive the data listening. This technique is triggered frequently without any synchronisation between the nodes. A lengthy preamble is utilised by the forwarding node to scan for polling of the receiving node. As a result, LPL which is sensitive to traffic rates reduces the network performance in situations of highly varying traffic rates such as data burst, even though it can be successfully optimised for identified periodic traffic rates. Key references are WiseMAC [4], X-MAC [5] and B-MAC [6].

WiseMAC utilised two communication channels, a data medium which uses TDMA and the control medium which uses Carrier Sensor Multiple Access (CSMA) to reduce idle listening. The periodic preamble is utilised to inform the receiving node of a packet. If the node displays a busy channel, at that moment it continues to stay awake to accept the packet or waits till the channel returns to silent. The major benefit of LPL deployed to BANs is the periodic sampling: it is effective for heavy traffic and unfixed traffic applications, but on body nodes where the periodic sampling is battery powered, it is not effective for low traffic. Also, no priority is allocated to the emergency traffic situation.

Sensor-MAC (S-MAC) [7] is an example of a schedule contention MAC created to tackle the energy wastage problem by periodic listening and resting. When the node is inactive, it will sometimes sleep, which is less energy-demanding than listening to the medium. It reduces the listening period by a way of sending the node into sleep state [5]. During this sleep state, a sensor node must switch off its radio in order to save energy. The S-MAC protocol transfer synchronisation data synchronises the sleep, wake and communication of packets with other nodes. The schedule consists of SYNC sleeping between surrounding sensor nodes. A packet has a period of listening and sleeping and starts with a wake time utilised in sending controlled packets. The schedule contention technique decreases the idle listening time, applying sleep schedules and operates in the same way for multi-hop WSNs. This protocol is used for high throughput systems.

Considering the basic requirements for WBAN reveals numerous needs for ultra-low power implants or on-body sensor nodes such as a defibrillator, and some other nodes not required to wake up frequently to exchange their schedules with remaining nodes. Schedule contention techniques may work perfectly well for on-body systems but they do not offer reliable solutions to manage emergency traffic and on-demand activities. Managing emergency activities needs new ideas that will permit implanted or on-body nodes to bring up-to-date the coordinator within a restricted period. Timeout MAC (T-MAC) [8] is arranged in slots and based on schedules and it is appropriate for reasonably high traffic applications but the early sleeping problem may result in data lost, especially long messages. In Proper MAC (PMAC) [9], the arrangement is in hybrid state and its functionality is based on listening where slack synchronisation of sleep time results in delay sensitive systems.

X-MAC [6] exploits the benefit of low power listening such as reduced power communication, simplicity and disengaging of the RF transmitter-receiver rest schedule. This protocol offers a continuation of short preliminary packets: each data packet holds the receiver address and residual amount of preambles. These preambles are forwarded at fixed intervals of time in a well-arranged format and the interval is sufficient to receive acknowledgement from the receiver. The operation at this stage is swiftly done in order to reduce energy at both the sending node and the receiving node.

Berkeley-MAC (B-MAC) utilised rest/listen cycles where the node listens to the channel for arriving packet transmission. In a situation where there is no data in the channel to be sent or an activity-free period this is detected by periodic checking by nodes using an LPL technique, unlike S-MAC where clock drift in nodes can have a great effect on communication [10]. To make sure the received information is concluded on time from its initial point, there is an introduction period of

100ms which is included after the radio wakes up. Due to the fact that all nodes cannot send packets at the same time rest time differs from one node to another.

Synchronisation does not occur in B-MAC, instead whenever there is a need to send data the node switches on the radio state and starts to forward an announcement. The announcement should be enough to make sure all nodes on the channel, irrespective of what mode they are in, can heed the signal. Thereafter, the forwarding node communicates the details of the receiving node and starts forwarding the packet.

Further, there is a TDMA protocol also found in WSN known as Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, a widely known protocol designed for larger networks [11]. Every node performs self-arrangement as well as a re-clustering function. Nodes will select a central node (CN) from the group of clusters and the node with more residual energy is selected as the CN, which is accountable for data aggregation and communication of packets to a coordinating node. Although the scheme targets energy saving and load stability it is not appropriate for a small number of wireless sensor nodes in BAN where clustering is not required, hence this makes it not within the scope of this work.

On the contrary, a TDMA MAC protocol contains an amount of timeslots distributed by a core node (coordinating node) to individual nodes that are within the network during network initialisation. The nodes send and receive data from the core node within its assigned timeslot. After this, it goes to sleep for the rest of the superframe: this is different from the contention approach where nodes stay collision free from their entire neighbourhood in the communication network. It supports efficient energy utilisation as far as strict synchronisation is in place to eliminate coinciding of timeslots. These timeslots are recurring in a static rotation known as a frame: an example of this technique is seen in the PB-TDMA protocol, where individual TDMA frames contain a preamble, which contains a devoted subslot for each individual node, and an information communication slot [12]. It is the responsibility of the node to listen to the media during the preamble and then communicate within the data communication slot [13].

These subslots are introduced to trigger the receiving node by way of broadcasting the receiving node ID of an outbound packet. When acknowledgment has occurred from the receiving node, the individual node switches off its radio when no data is available for transmission. This technique eliminates unwanted energy utilisation of nodes. The radio is activated whenever the node locates its ID in the preamble, or alternatively, if the node has data to communicate. However, the author stated that the PB-TDMA protocol performs better than the BMA protocol [14] for standard traffic but there are some difficulties linked to PB-TDMA, such as overhearing the preamble and restriction of managing emergency events. Considering BAN applications, resolving the difficulties may permit the heterogeneous BAN traffic in an energy efficient manner. Thus, contention-based CSMA MAC protocols such as S-MAC and WiseMAC are not energy-saving for WBANs for the majority of systems in eHealth: BANs such as posture monitoring have continuous periodic bandwidth demands. In addition, WBAN may need to support real-time systems such as critical event recording.

5. CSMA/CA versus TDMA

In the Carrier Sensor Multiple Access/Collision Avoidance (CSMA/CA) protocol, a node competes for the media to send data: when the medium is idle, the node sends its data, but when the medium is busy, the node defers its transmission. Scalability is associated with these protocols with no stringent synchronisation limitation but they suffer considerable protocol overhead. As mentioned in the previous section, in TDMA schedule-based protocols, the media are shared into timeslots of fixed or variable period. Nodes are allocated to these slots and individual sensor nodes transmit within their slot duration.

Traditional TDMA protocols outpace CSMA-based protocols in all aspects with the exception of the protocol adaptability to alteration in network topology [15]. However, traditional TDMA protocols require good synchronisation mechanisms. The implementation of such mechanisms is difficult, especially in an active network, where alterations in the network topology occur frequently. Since WBAN is not normally seen as an extremely active network, mainly dealing with fixed sensors' functionalities, this issue does not occur. Table 1 gives an outline of the comparison between TDMA and CSMA/CA protocols [15].

Table 1. Comparison between TDMA and CSMA/CA [15]

Attributes	**CSMA/CA**	**TDMA**
Power Consumption	High	Low
Bandwidth Utilisation	Low	Maximum
Preferred traffic level	Low	High
Dynamic ability (Network Changes)	Good	Poor
Effect of packet failure	Low	Latency
Synchronisation	Not Relevant	Crucial

6. Cross Layer Design

Design targeting energy efficiency in wireless sensor nodes means that the traditional approach to network protocol layering may not be the best in relation to energy management [16]. Usually in a network protocol model, there is a direct communication between layers which keeps the communication model under control when performing a networking task; however, [16] proposes a cross layer framework which optimises the various control parameters across the networking layer. These operations are implemented under the condition that all acknowledged packets must have delay less than the equivalent delay limit, while maintaining the overall distortion at a particular threshold assigned by the system. However, the MAC layer can adapt the communication energy in the layers such as the physical and application layers with a constraint on delay and bit priorities.

Lakshmisudha and Arun [17] suggest that more research should be geared towards more cross-layer optimization and if possible layers should be treated together. One key issue to consider when developing a protocol is that it should not be designed in isolation from other layers of the OSI model but should make use of the benefits of interdependence of one upon another. These interdependency parameters include compatibility with the current network, interlay and internodes communication. Similarly, flexibility gives more avenues for fast prototyping and positioning of sensor nodes, which may be applied for both BAN and WSN.

Cross-layer optimisation should permit network parameters to transmit and receive information between the physical layer and the protocol layer. However, the physical layer resolves the requirement for basic but robust modulation, communication and receiving methods. Kim et al [18] designed a novel version of a cross layer protocol which takes into account the MAC protocol in transmitting information between nodes and the central node. The objective of the protocol was to increase the life cycle of a sensor node while overcoming the hard energy limitation. An adaptive duty cycling approach was implemented, followed by an algorithm based on a tree structure which was utilised in enhancing the network lifespan.

A cross layer protocol approach such as the automatic request (ARQ) of link layer, data layer and the link quality has been discussed in detail in [17] and [19]. In fact, for MAC protocol design for BAN to benefit from cross-layer communication optimisation should be adaptive with reusable frame and network robustness.

The power source is another concern when it comes to cross layer design as the battery needs to be well matched to the application domain. This is particularly so, when the application is an in-body or on-body wireless node, where several years of unattended service are required for its functions of processing, sensing and transmitting. As discussed, conserving energy in such units has resulted in a search for options of saving energy and some of these include energy harvesting and energy storage technology. Several authors [20,21] have proposed ways of prolonging wireless sensor functional lifetimes through the use of clear protocol implementation, energy harvesting or battery modelling. Since it is possible to combine cross layer optimisation with energy harvesting, this will enhance the system life cycle.

Energy harvesters powering wireless sensor networks and energy demand reduction at various stages from hardware design to protocols for medium access control, data collection, and topology architectures have been implemented by various authors such as in refs. [20-24]. These are motivated by various design aims in improving maximum power tracking, simplified design and long span of energy backup, whereas there are still some areas for further optimisation. These areas include making full use of the harvester, rather than taking the rechargeable battery as the main source for the load, also employing the energy harvester only for charging or as the primary source [25].

7. Discussion

The study of energy efficiency in wireless sensor networks has been a very active research subject in recent years since it can improve communication performance. Rather than carefully designing dozens of sensor nodes or designing energy harvesting systems, the adoption of carefully implemented protocols in addition to the systems design is more practical and contributes to the overall network performance. Firstly, it can help to minimise energy consumption and extend communication lifespan. Secondly, the communication between nodes would be effective since the appropriate protocol is implemented and redundant use of the medium minimised.

8. Conclusion

Techniques for reducing energy drain in nodes in a wireless sensor network have been reviewed. This is an issue of general importance to WSNs, since the replacement of batteries powering nodes involves labour costs and nuisance considerations, potentially resulting in the failure of nodes due to the overlooking of battery replacement. This issue is particularly pressing in body area networks, especially with devices implanted in the human body. While energy harvesting techniques have a role to play, they are only able to eliminate the need for battery replacement if the energy drain caused by the node is reduced to a very low level. To effect this, it is necessary to adopt protocols that are tailored to the needs of the application, rather than using generalised protocols that may be more appropriate to nodes having higher data rates in circumstances where energy supply is not a problem. Several innovative MAC protocols have been identified in the literature and all have both advantages and disadvantages. The protocols LPL, S-MAC and B-MAC are particularly worthy of consideration, but it is evident that there is scope for further improvements, particularly focusing on TDMA rather than CSMA and then breaking away from the straitjacket of the OSI layer structure and using cross-layer design to maximise the opportunities to tailor a custom MAC to specific applications. The fundamental reason for the need for tailoring of application-specific MACs is the range of different requirements for sensor node data channels, since some nodes may only produce a very low data rate with no requirement for emergency reporting while others may need to be able to report urgent emergencies and still others may produce high data rates, although possibly not continuously. The key objective in a low-energy-demand MAC is to be able to reduce the node energy consumption to a very low level when there is no need to send data, but to maintain the channel in a ready state for data transmission.

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