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Power saving MAC protocols in wireless sensor networks: a survey

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ABSTRACT

In a wireless sensor network, energy is almost always the greatest limitation. Energy sources are restricted in many of the environments where nodes are deployed, limiting them to the use of batteries for power. Therefore, conserving energy is supremely important, however, such a task poses many challenges to hardware and protocol design. One of the greatest problems faced is reducing the energy consumption of the communications systems, which represents a substantial amount of the total consumption. This paper surveys the most recent schemes designed to reduce the communications module energy consumption with a focus on novel MAC protocols for ad-hoc wireless sensor networks. It initially describes the many challenges involved, then it analyses each protocol individually. Finally, the presented protocols are compared and the issues that remain open are raised for further research.

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1. INTRODUCTION

With the world's increasing reliance on technology and its integration in every aspect of our lives, subjects relating to internet of things (IoT) [1] have increasingly become more relevant. Wireless sensor networks (WSNs) [2] in particular have been used in a variety of applications such as monitoring patients in real-time inside healthcare facilities [3], enhancing emergency response [4], control lighting in urban scenarios [5], monitoring electric grids, and many others [6], [7].

A WSN is a network comprised of sensor nodes that use radio transmission to communicate with each other and gather data [8]. Such structures allow the collection of data from multiple spatially separated points at once and can be adapted to each specific situation. The properties it can measure include temperature, pressure, sound, pollution, and so on. Most WSN nodes are made to be cheap and small, containing sensors, communications, processing, and power modules. However, the specifics of the environment where they will be deployed significantly affect the node's composition, capabilities, restrictions, and price.

The design of a WSN faces many challenges [9]–[14], however, in general, power consumption is the greatest one [15]. Some applications allow for power generation on-site with solar panels and alike, but these produce a limited amount of power and do not work in all situations. Others require nodes to be fully battery-operated, with some kinds of nodes being discarded once the battery is depleted. Therefore, reducing energy consumption is a priority in WSNs. Data processing requires very little power in general, but the transmission of the data acquired, and especially idle listening consumes a much greater share of the available energy [16].

There have been many techniques to reduce power consumption developed throughout the years. Duty cycling [17], separate communication channels to wake up nodes in low power mode [18], clustering protocols [19]–[21], reworking the MAC protocol [22], and many others [23]. This paper explores the literature for ways to extend network lifetime with a focus on novel MAC protocols. The rest of this paper is structured as follows: section 2 discusses the challenges involved in improving network lifetime while section 3 explains many of the MAC implementations available and their characteristics. Section 4 analyzes the problems that remain unsolved and explore future research paths. Finally, section 5 concludes the paper.

2. INCREASING NETWORK LIFETIME IN WSNS

There are many things to consider when trying to increase the lifetime of a WSN [24], but most implementation focuses on the communication system as it consumes the most energy. Transmitting a single bit of data can consume as much energy as thousands of operations [25] while receiving and idle listening are of the same magnitude; thus, such operations should be avoided whenever possible.

To that end, many novel MAC protocols have been created. The MAC sublayer is a part of the Open Systems Interconnection Model (OSI) reference model. It controls how devices have access to the transmission medium which, in wireless networks, is shared by all devices, therefore rules need to be set to avoid interference. However, the separation of concerns provided by the OSI model is not ideal for WSNs, where optimization often supersedes modularity. As has been shown by previous research, adding information from different layers to the MAC protocol can greatly reduce energy consumption [26]. Because of that, some of the protocols discussed here may break OSI guidelines. The following are some of the challenges involved in reducing the communications system's impact on battery life:

– Duty cycling

To avoid wasting energy while there is no data being transmitted, nodes should minimize the communications module's active time. Usually, this is done by putting the transceiver in sleep (low power) mode. However, WSNs require inter-node collaboration to prevent areas of the network from losing connectivity when key nodes are inactive. It is also important to note that transitions between states can have associated costs [17]. In these scenarios reducing the total amount of transitions can further reduce energy consumption. Duty cycling can also increase the latency of the network and reduces maximum throughput, requiring extra added complexity to avoid these issues.

– Collision avoidance

Interference between transmissions is a concern in all shared medium networks, but they carry an additional penalty in WSNs. Retransmitting data costs energy and reduces the total network lifetime, therefore it must be avoided as much as possible. This is usually implemented by a MAC protocol, but the IEEE 802.11 carrier sense multiple access/collision avoidance (CSMA/CA) implementation requires continuous idle listening. Alternative contention-based MAC implementations focus on reducing the transmission and listening times while keeping collisions to a minimum.

Some MAC schemes utilize time-division multiple access (TDMA) to eliminate collision by giving devices specified time frames where they can transmit data. This is challenging to implement in ad-hoc networks since they require regular synchronization to prevent schedules from drifting and it introduces additional latency [16], but it provides great improvements and often can easily be adapted to include a sleep schedule. Other approaches use specialized preambles [27] or modification to the usual expectations of medium access control [28]. Both approaches eliminate the necessity of synchronization between nodes but come with their own set of challenges.

– Power balancing

Another factor to consider when designing a WSN is the fact that nodes consume more energy depending on their location and duties on the network. For example, route optimization causes traffic to be concentrated on certain paths. If this discrepancy is not accounted for, nodes in critical paths are likely to fail before the others, leading to loss of connectivity in entire sections of the network. Ideally, nodes would only fail when the entire network runs out of energy. This is such a concern that some WSN applications [29], [30] use minimum node lifetime as one of their main statistics. Considering the remaining energy available for a node (also called residual energy) when making decisions can slow down the growth of the energy gap between nodes but does not stop it. To achieve a better balance, protocols can shift their overhead between sender and receiver, leading one to spend more energy than the other.

– Mobility support

Most networks change over time. In a WSN nodes can be added, removed deliberately, removed due to failure or battery depletion. These events are infrequent and represent what is called weak mobility. Most wireless MAC protocols are built to handle such occurrences because they are a normal part of a network's lifecycle [31]. However, that is not enough in many situations. Some applications require support for deliberate and frequently moving nodes with minimal loss of connectivity or delay. This is called strong mobility and protocols that support it not only consider a node's connections to other nodes but also its position, velocity, and other factors depending on the specific situation where they are applied [32]–[36].

3. MAC PROTOCOLS FOR WSNS

Below the studied MAC protocols are briefly described, highlighting their benefits and flaws:

3.1. Sensor MAC (S-MAC)

S-MAC is a MAC procedure specifically designed for WSNs that includes a sleep schedule. S-MAC divides time into fixed-size frames, each having an active and a sleeping part. Nodes are free to choose their own schedule, but a new node will attempt to follow the same schedule as its neighbors to avoid control overhead. If it can't find any other nodes, it will choose an arbitrary timetable and broadcast it. Each node keeps a table of its neighbors' schedules and, when it wants to send data, it simply waits for its destination to be in the active part of the frame. To avoid collisions S-MAC uses the same request to send/clear to send (RTS/CTS) messages present in the IEEE 802.11 specification, forcing nodes to compete for the medium. While this scheme greatly reduces node awake time, the active part of the frame must be big enough to cope with the highest throughput required. This means that S-MAC wastes energy when not working at full capacity. Another problem arises when there is more than one schedule on the network, in this situation virtual clusters are formed and nodes at the edges of each cluster consume more energy due to having to wait long periods to transmit to nodes using other schedules [22].

3.2. Timeout MAC (T-MAC)

T-MAC aims to reduce S-MAC's energy wastage when not working at full capacity. It does so by dynamically modifying the length of S-MAC's active portion of the frame. When a node becomes active, it will send all the stored data it has and waits for a short period (TA). If it receives no messages to forward in that time, the node will go back to its sleep phase. The proposed procedure reduces node active time when the network is not working at full capacity and increases it to meet demand during activity spikes. However, the energy consumed during a TA period where it does not receive messages is still wasted [37]. Figure 1 illustrates the differences between T-MAC and S-MAC.

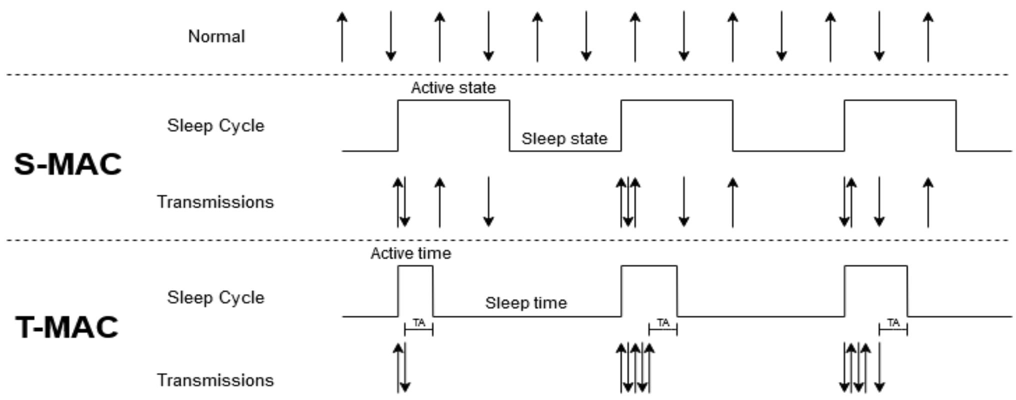

Figure 1. Comparison between S-MAC and T-MAC, adapted from [37]

3.3. Berkeley MAC (B-MAC)

The B-MAC protocol allows nodes to have completely independent sleep/wakeup schedules by using a CSMA-based system to transmit data between themselves. When a node wants to send data, it precedes the package with a preamble slightly longer than the sleep time of the receiver. Eventually, the receiver node will wake up, sample the medium, and, if it notices a preamble, it will remain awake to receive the transmission once the preamble is done. B-MAC offers much better throughput and battery life when compared to S-MAC. However, transmitting the preamble necessary for low power listening (LPL) cost a substantial amount of energy to the sender, and all receivers that sample the medium and find a preamble must stay awake until the preamble is finished to determine if they are the recipients of the message, causing a problem known as overhearing [38].

3.4. X-MAC

To improve on B-MAC's preamble approach, X-MAC attempts to mitigate its biggest drawbacks. To reduce the inefficiency caused by overhearing, the extended preamble is broken into smaller preamble packages that contain the ID of the target node. When a node wakes up, samples the medium, and finds a preamble, it checks the ID transmitted with it. If it is not the intended receiver, it will go back to sleep, otherwise, it remains awake. As a result of this, overhearing nodes can go back to their sleep mode much more quickly. Preamble strobing, the periodic insertion of small pauses in the preamble, is used to prevent nodes from having to wait until the end of the preamble to send/receive data. Such pauses allow the receiver to send an early acknowledgment (ACK) message to indicate that the transmission may be initiated. The resulting protocol is much more efficient than B-MAC and has lower latency [27]. Figure 2 compares X-MAC to LPL, the process used by B-MAC.

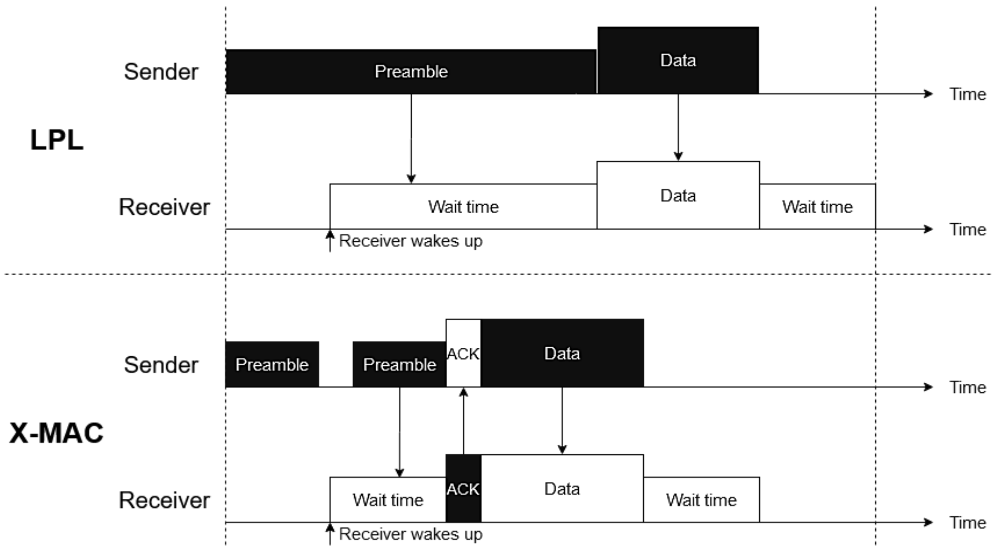

Figure 2. Comparison between LPL and X-MAC, adapted from [27]

3.5. BoX-MAC

BoX-MAC-1 and BoX-MAC-2 are a pair of protocols that build upon B-MAC and X-MAC, respectively. They improve their predecessors by including data from other network layers into their structure. The first uses a predominantly layer 1 (physical) approach: It packetizes B-MAC's long preamble and adds link-layer information, allowing nodes that are not the intended receiver of the message to return to their sleep mode earlier. The second uses a predominantly layer 2 mechanism that is very similar to X-MAC, but it replaces the package-based receive check with a layer 1 energy-based receive check. The resulting protocols are more energy-efficient than their predecessors, but each is better in specific situations. BoX-MAC-1 is more efficient in high volatility networks with little traffic while BoX-MAC-2 is better at handling high traffic with lower volatility [26].

3.6. Demand wakeup MAC protocol (DW-MAC)

The DW-MAC improves on the S-MAC implementation by fully integrating medium access control to sleep scheduling. Nodes using DW-MAC that want to transmit contend for the medium normally, but they replace the RTS/CTS messages with a scheduling frame (SCH) that is used to schedule a time during the next sleep period where they can send their data. The scheduled period is calculated based on how far into the active period the SCH was received. This process creates a one-to-one mapping between the active (data) period and the sleep period. Lastly, when the scheduled time is finally reached, the receiver and sender wakeup and complete the data transfer before going back to sleep. DW-MAC prevents data transmissions from colliding by exploiting the contention that happens in each active period. Since the mapping between the periods is one-to-one, once a node gains medium control by contention that automatically generates an interval during the sleep period where sender and receiver can communicate without collisions between data packages happening. As a result, DW-MAC has much lower latency and energy consumption, however, it does not specify a synchronization mechanism, requiring it to be implemented separately [16].

3.7. Receiver initiated MAC protocol (RI-MAC)

The RI-MAC flips the usual expectation of medium access control: The receiver checks for the existence of pending messages by sending a probe message (also known as a beacon). Senders with data to transmit listen for the probe, wait for it to finish, and then starts transmitting. By doing this, RI-MAC avoids having to send lengthy preamble messages like other asynchronous protocols do while using LPL. It also reduces the amount of time a pair of nodes occupy the medium before they reach rendezvous, which allows for more contending nodes to transmit, increasing potential throughput. Finally, overhearing is minimized because the receiver only expects to transmission within a short window after the beacon is sent [28].

3.8. Lifetime balance MAC (LB-MAC)

LB-MAC allows pairs of nodes to adjust MAC behavior to optimize network lifetime. Neighbor nodes communicate and shift the communication overhead to the one with the longest expected lifetime. The shifting of the overhead is done by controlling the receiver's channel checking period and the sender's retry interval. When the sender has a lower expected lifetime, the receiver increases its medium checking frequency to allow the sender to use a longer retry period while still guaranteeing rendezvous between the nodes. When the receiver has a lower life expectancy, the reverse process happens. The receiver leads the overhead shifting process and embeds the changes it makes to the connection's attributes in the ACK messages it sends to the sender, avoiding the necessity for extra messages. As a result, the minimal lifetime among neighbors is extended and the total network lifetime may be prolonged [39].

3.9. A-MAC

A-MAC is a receiver-initiated MAC protocol for low power networks. This protocol works similarly to RI-MAC but makes a few changes that improve its performance. First, it optionally allows for the use of multiple channels where one is reserved for beacon messages, and the remaining traffic is dispersed among the others. Secondly, it uses backcasts, a link-layer primitive that allows nodes to probe others in parallel and reliably distinguish between the case of zero replays (indicating no traffic) from the case of one or more replays (indicating pending traffic). This mechanism uses non-destructive interference, making it robust against collisions and overhearing. As a result, it allows the receiver node to make better decisions on whether to go back to sleep or remain awake to receive messages. However, most radios lack the hardware and software support necessary to properly implement A-MAC, requiring workarounds [40].

3.10. Asymmetric MAC (Asym-MAC)

Asym-MAC was created to deal with the problems posed by asymmetric links to receiver-initiated MAC protocols such as RI-MAC and A-MAC. Asymmetric connections exist when the reliability or throughput of the channel in one direction is smaller than in the other direction. At manageable levels, asymmetry can increase the probability of losing probe messages, leading to delays and a lower package delivery ratio. At its extreme, it can lead to the communications channel essentially becoming unidirectional and completely prevent receiver-initiated MAC from working. Asym-MAC remediates this by employing a hybrid approach. By default, all links are in R-mode (receiver-initiated), however, if a sender fails to receive the probe multiple times, it will become T-mode (sender-initiated) and the sender will transmit its data before going back to R-mode. The receiver is notified of the change in mode using a clear channel assertion (CCA) period added at the end of each probing package. During this period, the receiver briefly checks for potential preamble packages, which signify the mode change. The more asymmetric a connection, the better Asym-MAC is when compared to other receiver-initiated MAC protocols. These improvements to package delivery ratio slightly increase Asym-MAC's average energy consumption (by around 2.6%) when compared to A-MAC on low asymmetry scenarios, but it greatly improves network reliability and delay times. Asym-MAC is also more energy-efficient than sender-initiated protocols like BoX-MAC [41]. Figure 3 illustrates Asym-MAC's mode transition.

3.11. CSMA/CA and TDMA hybrid MAC protocol (CTh-MAC)

The CTh-MAC is designed to improve energy efficiency in 3D mobile WSNs. Nodes are allocated into concentric spherical subsets based on their distance to the network gateway. The allocation algorithm also considers the velocity of each node, predicting its future position to optimize the subset formation. Subsets communicate with the gateway according to a TDMA schedule. Outer subsets go first with inners ones serving as relays to the network sink. When it is the turn of a given subset, its nodes content with one another to access the gateway in a CSMA/CA fashion. The resulting network has considerably better throughput and longer lifetime when compared to other hybrid approaches. However, this protocol assumes that all sensing nodes are within the transmission range of the base station so that it can gather information on their positions [36].

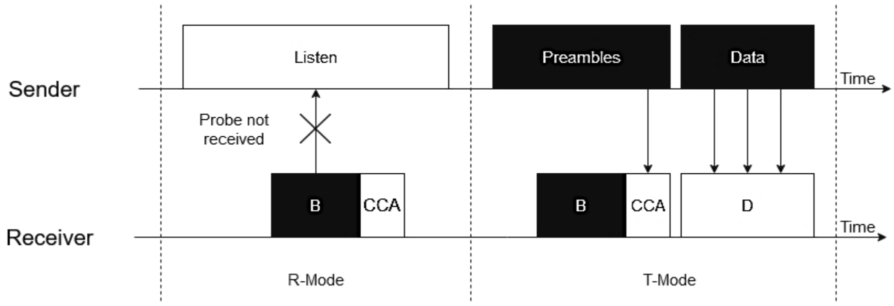

Figure 3. Asym-MAC mode transition, adapted from [41]

Table 1 summarizes the characteristics of the protocols studied. Below, the columns of the table are briefly discussed:

– Synchronicity: Refers to a protocol's necessity to use synchronization mechanisms to prevent drift between node schedules.
– Clustering: Clustering happens when groups of nodes have different properties from one another. In some cases that can lead to nodes at the edges of clusters consuming more energy, but CTh-MAC deliberately causes this kind of division as part of its operations.
– Sender or receiver-initiated: In sender-initiated MAC protocols, the sender initiates the data transfer process. The opposite happens in receiver-initiated ones.
– Impact of asymmetric links: Describes the problems that may arise when the connection is asymmetric. Sender-initiated protocols are not affected by asymmetric links.
– Mobility support: Determined by a protocol’s general ability to deal with changes in the network structure.

Table 1. Comparison between MAC protocol

Protocol	Year	Synchronicity	Clustering	Power-Balancing	Sender or receiver-initiated	Impact of asymmetric links	Mobility support
S-MAC	2002	Synchronous	Yes	No	Sender-initiated	None	Weak mobility
T-MAC	2003	Synchronous	Yes	No	Sender-initiated	None	Weak mobility
B-MAC	2004	Asynchronous	No	No	Sender-initiated	None	Weak mobility
X-MAC	2006	Asynchronous	No	No	Sender-initiated	None	Weak mobility
BoX-MAC	2008	Asynchronous	No	No	Sender-initiated	None	Weak mobility
DW-MAC	2008	Synchronous	Yes	No	Sender-initiated	None	Weak mobility
RI-MAC	2008	Asynchronous	No	No	Receiver-initiated	High chance of probe loss	Weak mobility
LB-MAC	2012	Asynchronous	No	Yes	Sender-initiated	None	Weak mobility
A-MAC	2012	Asynchronous	No	No	Receiver-initiated	High chance of probe loss	Weak mobility
Asym-MAC	2014	Asynchronous	No	No	Receiver-initiated	Changes to the sender-initiated mode	Weak mobility
CTh-MAC	2018	Hybrid	Yes	No	Sender-initiated	None	Strong mobility

4. OPEN ISSUES

Although the studied protocols have greatly improved energy consumption and reduced the constraints that arise from a restricted power source, there are still issues that remain unsolved. Most notably, power balancing has been absent from most of the examined schemes. It may be possible to adapted LB-MAC’s approach of shifting the overhead of communications between sender and receiver to other asynchronous protocols, including receiver-initiated ones. However, adapting it to be used in synchronous communications presents many challenges because of the rigid schedules employed in this kind of communication. Likewise, its integration with approaches from other layers is still untested [39]. If possible, upper layer schemes such as the improved energy-efficient clustering protocol (IEECP) [20] could be used to balance traffic and reduce transmission distance while LB-MAC balances power on each node pair.

While receiver-initiated MACs are some of the most efficient protocols studied, it is also important to point out that current implementations are limited by the hardware available. A-MAC specifically would benefit from native support of the backcast primitive or processors with memory-mapped radios. The creators of A-MAC estimate that these features could reduce idle listening power by 40% [40].

5. CONCLUSION

This paper surveys MAC protocols designed for wireless sensor networks, focusing on their capability to extended network lifetime. First, we introduced the challenges involved in the design of such protocols and outlined some common solutions. Studied factors include duty cycling, collision avoidance, power balancing, and mobility support, all of which can heavily impact the network's battery consumption. Then novel MAC implementations were analyzed and compared to determine their strengths and weaknesses. The analyzed protocols were classified according to their synchronicity, power balancing support, and many other characteristics. Finally, the biggest remaining issues and possible paths of future research were raised.

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