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MAC Protocols for Application-Specific Wireless Sensor Networks: A Study

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***Abstract*—Subsequent to introduction of Wireless Sensor Networks (WSNs) it remain an active research topic due to their wide variety applications in areas such as healthcare, military, monitoring, surveillance and many more systems. In most applications, sensor nodes are inhibited in energy supply and communication bandwidth. Therefore, novel techniques to reduce energy inefficiencies and for efficient use of the limited bandwidth resources are essential. Such constraints combined with intense network operation create several challenges to the design and management of WSNs and require energy-consciousness at all layers of the networking protocol stack. For example at the Data-Link layer, low duty cycle Medium Access Control (MAC) protocols trade off latency for energy efficient operation. In this paper, we present a survey of modern low duty cycle MAC protocols. We first summarize the design challenges for MAC protocols in WSNs. Then, we present a widespread survey of the most important and recent MAC protocols. These protocols are classified into synchronous and asynchronous based on their mode of operation. Finally, the paper emphasizes open research problems in MAC layer for WSNs.**

***Index Terms*—Wireless Sensor Networks; Linear Sensor Networks; Chain-type sensor networks; Duty-cycle; MAC protocols.**

I. Introduction

The wireless sensor network (WSN) is a well-proven advanced technology that aims to expand human-oriented applications in large-scale remote sensing. Such networks are used in various applications to provide accurate estimates where the presence of a person is complex, dangerous and / or costly. This technology can be implemented to monitor large-scale environments such as international border surveillance; tracing of railways, detection of leaks in gas / oil / water pipelines, search and rescue from natural disasters, flood warning systems, etc. All these applications have a common topological structure that is internally linear. This is the result of a carefully controlled and planned deployment of sensor nodes for careful monitoring of a controlled environment, which is linear in nature. We consider this class of networks as WSN linear or LWSN. Alternatively, in some studies this WSN class was called WSN-type. Linear / chain network properties represent a number of special problems and new design requirements that need to be addressed.

The purpose of this study is to examine the relevant MAC protocols that apply the work cycle function that can be used / modified to meet the needs of LWSN applications. In the next section, new problems related to the linear structure of the network are discussed with respect to the MAC protocols. Then in Section III, we'll look at the MAC protocols of the work cycle, which are classified as synchronous and asynchronous. In this review, we evaluate the suitability of these protocols for LWSN. We define optimization methods for your work to solve special properties of LWSN. We also determine their common strengths and weaknesses with respect to classic WSNs. In Section IV we present our main findings related to the development of a new MAC protocol specific for LWSN [1]. Section V concludes the document and highlights future directions of research.

II. Challenges Caused by LWSNs

Providing end-to-end communication with low cost with an acceptable delay in the delivery of data is the main objective of WSN. These problems are reinforced in LWSN, since the linear topology limits the number of neighbors and, consequently, a possible transmission route, which makes data loss more likely than in classic WSNs. Typically, LWSNs suffer from unbalanced data traffic between nodes, for example, nodes closest to the sink are usually more congested than nodes further down. This is due to the use of the multi-hop approach, which is used to transfer data from nodes that cannot directly reach the receiver. As a result of the failure in the data transmission, the data is significantly increased due to congestion and increased communication delays due to frequent retransmissions [2].

Uneven load distribution across the network becomes more evident during the life of the network. The nodes closest to the shell suffer from more energy depletion than the nodes furthest from the shell. In this case, the network can be terminated prematurely due to disconnection of communication lines with the receiver [3]. In addition, to ensure continuous communication and a small communication delay, nodes around the receiver cannot sleep often or for a long time and must be available to perform their relay functions [3].

In LWSN, node failure has serious implications for the overall functionality of the network in terms of network coverage and connectivity. In classic networks, the redundancy of routes provides the reliability necessary to overcome the node failure problems. However, LWSNs are characterized by dispersed implementations, which require careful planning of how the resources of each node are used. This problem can be solved with the use of innovative MAC protocols to save energy nodes and equitable distribution of workload between multiple nodes. Reducing node failures due to energy depletion and ineffective use of bandwidth helps avoid the most serious problems, such as communication and security holes. Holes for connection can divide the network into several disconnected segments, which are isolated from the sink. In [5, 6], two approaches were proposed that address the failure and restoration of a node in LWSN.

In addition, access to channels in LWSN tends to be more complex, which results in buffer overflow and packet loss [3, 7], which results in additional packet loss and higher latency, to the extreme [8]. Some researchers have proposed the introduction of resource-rich devices around the receiver to solve resource availability problems. However, the implementation of different types of nodes is not always a viable solution [9].An additional problem with the linear structure of the network is the problem with the exposed/hidden terminal. Open and hidden problems with the terminal cause communication conflicts, which leads to increased latency and data loss. In the field of classic WSN studies, some researchers have investigated open and hidden terminal problems, for example, [10] and [11].

On the other hand, the unique properties of LWSN can offer many potential benefits for improving network performance and lifetime. For example, prior knowledge of neighboring neighbors on the upstream / downstream allows the workload schedule to determine message transmission intervals [12]. In [13, 14] the authors present a mechanism for using advanced knowledge about the structure of the network in optimizing the functioning of the MAC protocol. Some specific implementations, for example, [15], where nodes are placed at equal distances, can significantly benefit from knowing the structure of the network in their localization and synchronization processes. To illustrate, since the topology is already known, additional management overhead for network discovery can be reduced, making it unnecessary to use thread-binding methods in LWSN.

III. Duty Cycle MAC Protocols

In this segment, we audit the obligation cycle-based MAC conventions. Such conventions apply rest/wake cycles to spare vitality by setting hubs to rest out of gear listening periods [21]. Killing hub's radio while hubs are enjoying some downtime can diminish the pointless power utilization by up to [22]. The obligation cycle MAC conventions exchange off inertness for vitality productive activity. Creators in [23] demonstrate that there is a critical vitality sparing in sending hubs to rest and sit out of gear tuning in. The Fig. 11 demonstrates the radio power utilization of MICA2 bit in various radio modes [23].

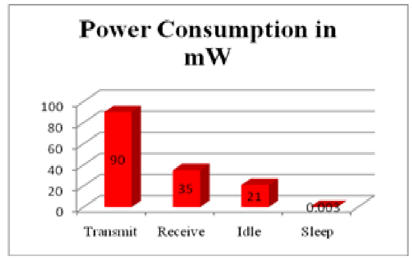

Fig. 1. Radio power utilization of the MICA2 bit sensor [23]

In this paper, we classify WSNs obligation cycle MAC conventions into synchronous and offbeat. Synchronous conventions make a timetable for hubs to indicate their rest and wake up times. Offbeat or unscheduled plans are additionally ordered into transmitter-started and collector started. When utilizing a transmitter-started approach, a hub sends visit transmission ask for bundles, a short introduction or the information parcel themselves, until one of them "hits" the listening time of the goal hub. In the beneficiary started approach, hubs send visit parcels demands, short preface or affirmation, to advise the neighboring hubs about the status of the hub to get bundles. In the accompanying two sub-areas we examine the most conspicuous and ongoing conventions in these two classes.

A. *Synchronous Low Duty Cycle MAC Protocols*

Each node has two modes, namely wake and sleep. In wake cycle, nodes will listen to the medium for synchronization requests and data packets. Where in sleep mode, nodes turn their radio off until the next scheduled wake up time.

I 2001, Pei and Chien introduced Power Aware Clustered Time Division Multiple Access (PACT) to utilize passive clustering, where nodes perform as the backbone of the communication [28]. Nodes are classified as, Normal node, Cluster Head, and Inter-cluster Gateways. Cluster Head nodes and Inter-cluster Gateways rotate their duty to avoid power depletion. Energy consumption caused by synchronization overhead increases as the network grows in size. This is due to nodes listening to the medium to get control packets from other nodes. In addition, any node with data ready to be transmitted will create its path to the sink before transmitting, which increases the data delivery latency.

One early energy efficient and most cited duty cycle MAC protocol is Sensor-MAC or S-MAC [22]. S-MAC is a complex protocol that applies periodic sleep-wake cycle to IEEE 802.11 for WSNs to reduce energy consumptions and support self-configuration [29]. The design of S-MAC assumes that applications will have long idle periods and can tolerate some latency. This makes S-MAC unsuitable for the class of applications requiring prompt reporting. It assumes that nodes do not need to be in wake/standby mode all time. Instead, its group all nodes in flat manner and arrange them by synchronizing the sleep/wake schedules of neighboring nodes. Nodes also maintain their sleep/listen cycles schedule by creating a schedule table for each node to update its neighbor's schedule. As a result, neighboring nodes may have same time slots for transmissions. Idle nodes will go to sleep during transmissions of other nodes. The listening period contains SYNC and DATA messages. SYNC is a packet to synchronies one node with its neighbors. While DATA message is for data transmission using the handshake methods of Request-To-Send (RTS)/ Clear-To-Send (CTS).

S-MAC utilizes a combined contention scheme and scheduling for collision avoidance. In addition, interfering nodes will go to sleep when they received control message to avoid overhearing. In S-MAC, long messages will be divided into small fragments in order to be sent as burst [22]. This method creates more messages to send, which requires longer access to the medium. S-MAC was designed mainly to reduce energy consumption, but it ignores other important performance factors, such as fairness, throughput, bandwidth utilization, and latency [30]. Fairness will degrade (MAC level perspective) as some nodes with small date will need to wait MAC with adaptive listening, messages move two hop in each duty cycle [30]. As a result, latency gets higher as more messages are waiting to be sent.

T-MAC [32] was introduced to improve the performance of S-MAC by using a dynamic duty cycle instead of a fixed one. The idea is to transmit all message from one node to another in bursts of variable length, and to sleep between bursts for further energy saving. It also determines the length of variable load by maintaining an optimal time. T-MAC applies RTS and CTS method. When RTS did not get CTS response it would try again before giving up. As in S-MAC, T-MAC can only send the message to one hope every duty cycle, which result in high latency. In addition, T-MAC has an early sleep problem, as a node switch to sleep even when a neighbor has some message waiting to be sent. As a result, the throughput is decreased in nodes to sink transmission. RMAC [32] is similar to S-MAC as sensor nodes have three moods in each cycle (SYNC, DATA, and SLEEP). It differs from S-MAC by sending a pioneer frame (PION) during the DATA mode to reserve the channel in the SLEEP cycle to send the message through many nodes in one duty cycle. PION is doing RTC and CTS respectively, and continues through the network until the end of DATA cycle, or the PION reached its target.

Building on RMAC, P-MAC [33] proposed to send multiple messages per duty cycle. That has given better traffic handling advantage over RMAC. P-MAC divides the network around the sink node by using Grade Division and Scheduling Assignment (GDSA). Each node sets up its schedule according to the grade it belongs to. Nodes that are located in the same grade will maintain the same scheduling time. This schedule is staggered with lower and upper grades. P-MAC use pipelining to forwards packets from upper to lower grade to reduce the network latency. RTS in P-MAC contain grade information, thus only nodes from lower grade can respond with CTS. In addition, Contention Window (CW) used to avoid contention when more nodes reply with CTS. Critical analysis for this protocol required. The Table-1, summarizes the features of the reviewed synchronous duty cycle MAC protocols.

B. *Asynchronous Low Duty Cycle MAC Protocols*

Barkley MAC or B-MAC [34] is an asynchronous duty cycle MAC protocol. In B-MAC, each node has its independent duty cycle scheduling. Node can transmit by sending a

TABLE I
A SUMMARY OF THE FEATURES OF THE REVIEWED SYNCHRONOUS DUTY CYCLE PROTOCOLS

Protocol Name	Target Applications	Key Design Ideology	Strengths	Weaknesses
S-MAC	Bursty event Multi-hop	Fixed low duty cycle preserve NAV for virtual carrier sensing (virtual clustering)Use physical/virtual carrier sense with randomized carrier sense time, RTS/CTS replace and NAV to avoid overhearing	Low duty cycle to accumulate energy Virtual clusters to maintain scalability and self-configuration Overhearing avoidance to save energy Message passing to reduce contention latency	High latency due to cyclic sleep Fixed duty cycle not adaptive to dynamic traffic loads
T-MAC	Dynamic traffic loads in time and location Multi-hop	Transmit messages in burst of inconsistent lengths Adaptive duty cycle (ADC) with timeout method dynamically ending the active part Future request-to-send(FRTS)Full-buffer priority with threshold control	Save additional energy by the adaptation to dynamic traffic	ADC increase latency and reduce throughput complex to distinguish the communication pattern of a live WS
R-MAC	Continuous monitoring Multi-hop	Exploits cross-layer information for subsequent forwarding of data frame Avoids data collisions through reservation of time slots Adjusts the period of the sleep and active periods according to the traffic loads	Energy-efficiently in high traffic loads Data collision rate is low despite the traffic loads	Proposed GTS packets effect sleep latency in the neighboring nodes
P-MAC	Continuous monitoring Multi-hop	Support pipelining for WSNs Using GDSA at the network layer to divides nodes into grades around the sink RTS and CTS differs from IEEE802.11 as RTS packet contains node grade info and by using the CW when receiving CTS	Cross-layer Energy-competently in high traffic loads Data collision rate is low regardless the traffic loads	Does not develop linear topology in the network.

preamble along with the data packet, which must be longer than the receiver's sleeping time, to make sure that the receiver will be in wake up mode. If a node is in a wake cycle, it samples the medium only when a preamble has been detected. Power consumption, throughput and latency are improved in B-MAC, however, overhearing and the long preamble are major drawbacks.

X-MAC [26, 35] was proposed to overcome the drawbacks of B-MAC. It uses short preambles to avoid the overhearing problem. The preamble contains the target address to help untargeted nodes to sleep and allow the targeted node to send early ACK. This not only avoids overhearing but also reduces the latency by half. The lack of flexibility is the main drawback of this protocol as it is very hard to reconfigure it after deployment. Another problem with this approach is that it fails to take the traffic caused by the preamble transmissions into account. The power efficiency is effect when the traffic built up, as the wireless medium will be occupied by the preamble transmissions.

RI-MAC [36] uses the receiver initiated mechanism to achieve lower power consumption, higher throughput and packet delivery ratio. Similar to B-MAC, each node has its independent duty cycle scheduling. The key difference compared to B-MAC and X-MAC is that the sender in RI-MAC stays in active mode until the targeted receiver is ready and the message start to be delivered. Receiver will inform the sender by sending beacon frame. The Table-2 summarizes the features of the reviewed asynchronous duty cycle MAC protocols.

IV. Analysis and Discussion

The existing general-purpose duty cycle MAC protocols designed for classical WSNs dramatically decrease the overall network throughput when applied to LWSNs. Researchers focused on power saving as a priority above all requirements. All previously reviewed methods suffer from some serious limitation when considering time critical applications. The real issue is to improve the network latency without sacrificing the energy. In classical WSNs, many factors, e.g., nodes mobility and network density, affect the protocol timeliness [37]. However, nodes mobility and high network density do not exist in static LWSNs deployments. Therefore, problems related to these factors, such as collisions, can be simply ignored when designing protocols for LWSNs.

Most of duty cycle MAC protocols reviewed here are designed without considering the impact of the network layer on the overall system performance. In addition, some LWSN specific protocols have attempted to solve some of the challenges specific to LWSNs from an application specific perspective. Therefore, there is no such work that addresses all the mentioned challenges in one generic framework. For instance DiS-MAC [10] was designed specifically for motorway surveillance application using directional antenna for message transmission in one direction. This approach does not suite applications that have transmission flow in both directions as the case in most linear applications. Some other approaches improved the network throughput at the expense of high power consumption, e.g. LC-MAC [2] and Wi-Wi [39]. Other approaches such as CSMA/CA [40] and DiS-MAC have not considered the time critical applications.

Oliver and Fohler [37] claimed that bounding end-to-end delays can be achieved in real deployment only 'When the network enforces deterministic behavior on each communication layer', or in "perfect" or "fixed" network topology. The key problem with this explanation is that the network will have over-constrained properties, which contradict with the nature of classical WSNs and LWSNs. End-to-end delay can be improved at MAC layers when using neighbor synchronization and periodic sensing, however this is expensive in terms of energy consumption. Application requirements can affect the trade-off between the network resources and network overall performance. For example, to

TABLE II
A Summary of the Features of the Reviewed Asynchronous Duty Cycle Protocols

MAC protocols	Target Applications	Key Design Ideology	Strengths	Weaknesses
B-MAC	Event monitoring with a wide range of network conditions	CSMA-based, Sleeping schedule can be adjusted to adapt the changing traffic loads by developers.-Adaptive preamble sampling scheme-A set of reconfigurable parameters of MAC protocol-A well-defined flexible interface	High throughput and energy efficiency-Allow to reconfigure a set of parameters of a MAC protocol based on the current traffic loads	Long preamble may introduce additional latency-No protection mechanism against the hidden terminal problem
X-MAC	Event monitoring with dynamic traffic loads-Multi-hop	Employs strobe preamble approach by transmitting series of short preamble-Address information embedding in short preamble for target receiver-Adaptive duty cycle to dynamic traffic loads	Overhearing problem reduced-Cut the preamble allows for lower latency and saves transmitter and receiver energy-Adaptive to dynamic traffic loads	The problem of hidden node still not solved due to using CSMA protocol
Wise MAC	Low and medium data rate-Multi-hop	Reduce the length of wake up-preamble-Sampling schedule exchange among neighbors Sampling schedule of the direct neighbor's knowledge is exploited for smaller wake upsize	Decoupling sender and receiver removes synchronization overhead Sampling schedule exchange allows just-in-time preamble and data transmission	Overhearing problem in non-target receivers End-to-end delay over multi-hop path

achieve timeliness in high priority message, networks should allow the extra usage of transmission in order to get the message to the sink faster. Using two different nodes capability along with the appropriate communication and segmentation methods can overcome these issues. Therefore, our new work is proposing a new communication protocol to deal with time critical applications without sacrificing the power efficiency.

Based on our study we observed that asynchronous MAC protocols are more scalable than synchronous MAC protocols. Frequent re-synchronization results in higher energy consumption. When global synchronization is necessary, the cost of re-synchronization may exceed the cost of keeping the nodes on at all times. Many of the problems present in existing MAC protocols, e.g., congestion, collisions, end-to-end delays, etc., are a result of the dense node deployment. In LWSNs, the overhearing, interference and collision problems are far simpler than those in classical WSNs. Therefore, developing an effective LWSN MAC protocol can simply be a problem of optimizing an existing general purpose protocol, i.e., the complexity of MAC protocols for classical networks is to deal with problems that are less severe, or even do not exist, in LWSNs.

V. Conclusion

This paper displayed an audit of a particular class of MAC conventions that actualizes obligation cycle component. This survey dissected the quality and shortcomings of these conventions. The emphasis was on evaluating the reasonableness of these conventions to LWSNs. In particular, the writers attempted to set up which LWSN prerequisites are now met and how the current conventions can be improved to suite LWSN applications. One of the principle discoveries was that while most existing conventions accomplish great outcomes in vitality investment funds, the inopportuneness prerequisite was not generally met. Inopportuneness, in many checking applications, for example, outskirt observation can decide the accomplishment of the framework. In addition, the greater part of the ebb and flow look into centers around hypothetical design of the system, or the sending of hubs making either a framework with high likelihood to lose its main goal, or high asset prerequisites in the arrangement [41]. The proposed arrangements really not tackling the correspondence issue, which is the fundamental worry in these applications. Along these lines, a cross-layer correspondence conventions is yet to be actualized. Besides, none of the current work has given a reasonable nonspecific structure considering the absence of assets and time affectability of the application. Any new MAC convention should exploit the LWSN includes and consider the application necessities to accomplish high vitality sparing and high productivity.

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