A comprehensive study of IoT and WSN MAC protocols : research issues, challenges and opportunities

Kumar, Arun; Zhao, Ming; Wong, Kai-Juan; Guan, Yong Liang; Chong, Peter Han Joo

2018

Kumar, A., Zhao, M., Wong, K.-J., Guan, Y. L., & Chong, P. H. J. (2018). A comprehensive study of IoT and WSN MAC protocols : research issues, challenges and opportunities. IEEE Access, 6, 76228 - 76262. doi:10.1109/ACCESS.2018.2883391

https://hdl.handle.net/10356/103391

https://doi.org/10.1109/ACCESS.2018.2883391

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 10, 2018, accepted November 19, 2018, date of publication November 26, 2018,
date of current version December 27, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2883391

A Comprehensive Study of IoT and WSN MAC Protocols: Research Issues, Challenges and Opportunities

ARUN KUMAR[1], (Member, IEEE), MING ZHAO[2], (Member, IEEE), KAI-JUAN WONG[3], (Member, IEEE), YONG LIANG GUAN[4], (Member, IEEE), AND PETER HAN JOO CHONG[5], (Member, IEEE)

[1]Department of Computer Science and Engineering, National Institute of Technology, Rourkela 769008, India
[2]Institute for Infocomm Research, Agency for Science, Technology and Research, Singapore 138632
[3]Singapore Institute of Technology, Singapore 138683
[4]School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798
[5]Department of Electrical and Electronic Engineering, Auckland University of Technology, Auckland 1142, New Zealand

Corresponding author: Ming Zhao (zhao_ming@i2r.a-star.edu.sg)

This work was supported by the NTU-NXP Intelligent Transport System Test-Bed Living Lab Fund from the Economic Development Board, Singapore, under Grant S15-1105-RF-LLF.

ABSTRACT Recent advances in wireless technologies, micro-electro-mechanical systems, and embedded systems enable the popular usage of the Internet of Things (IoT) and wireless sensor networks (WSNs) in many important applications, such as smart buildings, security, target tracking, industrial automation, and so on. Typically, a WSN consists of a large number of tiny, low-cost sensor nodes that are limited in terms of their capabilities of computation, communication, memory, and power. In WSNs, energy-efficient algorithms are of paramount importance for a long lasting high throughput network. MAC protocol plays a prominent role in extending the life-time of WSNs. MAC protocols provide various schemes on how multiple nodes access a common wireless medium. To achieve a longer lifetime for the nodes and the networks, MAC protocols need to be energy-efficient and reduce the sources of energy wastage. Energy conservation in sensor nodes is generally achieved by duty cycling the radios, and it is the MAC layer protocol that controls when to switch on and off the radio. In this paper, we discuss the essential properties of MAC protocols, the MAC for IoT and the common causes of energy consumptions. Thereafter, we categorize the MAC layer protocols and discuss several protocols under each category in depth, emphasizing their strengths and weaknesses, and giving a detailed comparison of MAC protocols. Finally, we conclude the survey with the insights on future research directions.

INDEX TERMS MAC protocols, wireless sensor networks, Internet of Things, energy-efficient and energy conservation.

I. INTRODUCTION

Recent development of tiny, low-power, low-cost, and multi-functional wireless sensor nodes has been accelerated by advances in manufacturing, electronics, communication, and miniaturization [1]–[3]. These sensors nodes are equipped with the capability of environmental sensing, data collection, data processing, and wireless communication. Therefore, wireless sensor networks (WSNs) can actively collect information and report events in a self-organized manner. WSNs has been widely used in a diverse range of applications, such as tracking, video surveillance, remote monitoring, localization and event-reporting [4]. Recently, there are increasing research efforts on WSNs towards energy conservation, which reduces the requirement on memory and the complexity of protocol design with the rise of the Internet of Things (IoT) [5]. In recent years, the number of embedded devices has increased and finally, they are envisioned to seamlessly connect to the Internet as the IoT [6].

A typical wireless sensor network is composed of several sensor nodes and one sink node. Sensor nodes collect data and forward the data to the sink node. A typical architecture of a WSN is shown in Figure 1. Sensor nodes sense the environment and collect raw data [7]. With local processing, sensors

TABLE 1. Typical sensor network application.

	Military	Habitat	Business	Public/ Industrial	Health	Environment
Tracking	Enemy Tracking	Animal Tracking	Human Tracking	Traffic Tracking	——	——
Monitoring	Security Detection	Animal Monitoring	Inventory Monitoring	Factory /Inventory/Machine Monitoring	Patient Monitoring	Weather/ temperature monitoring

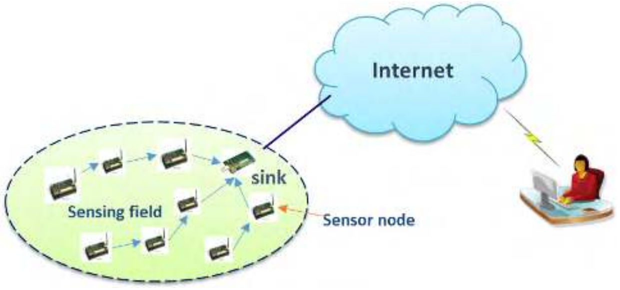


FIGURE 1. An architecture of a wireless sensor network.

communicate with each other. If necessary, data aggregation is performed and the aggregated data is delivered to a sink. Users can have access to the data collected from sensors through the sink node by accessing the internet [8].

Sensor networks are often multi-hop and communication is typically data-centric rather than node or address centric. Sensor networks often have a many-to-one traffic pattern, which leads to a ''hot-spot'' problem. Sensor networks should maintain a certain quality of service [9], [10]. The limited power, low radio range, potentially high density and an ever-changing environment pose difficulties in the design of efficient protocols for WSNs.

WSNs have covered a diverse range of applications, such as, but not limited to, industrial process monitoring and control [11], [12], environment observation and habitat monitoring [13]–[15], healthcare applications [16]–[19], home automation [20]–[23], traffic control [24], [25] and forecast systems [26]–[28]. Table 1 provides an overview of WSNs applications.

In many applications, WSNs are required to operate for several years without human intervention. However, sensor nodes are energy constraint. Nodes in a sensor network start to become disconnected, once the energy of sensor nodes drains out, resulting in performance degradation of the network. Therefore, prolonging the lifetime of the network is crucial for network performance.

MAC protocols have a significant impact on the energy consumption of sensors. MAC layer is a subset of the Data Link Layer, the second layer of the OSI model, which is directly above the Physical layer, the first layer. Since the MAC layer controls the radio, and radio is the one that consumes energy the most, MAC protocols largely affect how the overall energy is spent, hence determining the node's lifetime [29]. The role of MAC protocols is to decide how nodes get an exclusive access to the shared medium and to ensure that only one node access the channel at a time. In addition, MAC protocols control the scheme for channel sensing, and collisions can be reduced with efficient design of MAC protocols. Furthermore, MAC protocols define the duty cycle for sensors, playing an important role in mitigating idle listening, so as to conserve energy. Therefore, an energy-efficient MAC protocol can prolong the lifetime of sensor networks significantly [30]. To address the demand, a large number of MAC protocols for WSNs have been proposed. It is essential to understand the features of existing MAC protocols before the design of new protocols.

To summarize the existing approaches of MAC protocol design, a multitude of survey work on WSN MAC protocols has been conducted. However, a comprehensive study on WSN MAC protocols with a focus on the energy efficiency in design is still missing in previous survey work. The research work in [31] investigates several MAC protocols proposed in the literature, and this survey categories MAC protocols with different medium access strategies, i.e., static access and random access. The survey in [32] presents the summary of the designs of several recently developed MAC protocols for WSNs. With a categorization of schedule-based and unschedule-based WSN MAC protocols, the work in [33] analyses the approaches that these MAC protocols apply to fulfil the requirements and support the characteristics of WSNs. The survey in [34] summarizes WSN MAC protocols and categorize them based on the problem that they are proposed to solve. The work in [35] presents a review of MAC protocols by classifying them into asynchronous, synchronous, frame-slotted and multichannel-based categories.

This survey focuses on medium access control (MAC) layer protocols for WSNs. The main contribution of this paper is to provide an exhaustive survey of the energy-efficient MAC protocols for WSNs as well as their classification into four main categories: asynchronous, synchronous, TDMA-based and FDMA-based protocols. Figure 2 shows the taxonomy of WSN MAC protocols that are presented in this paper. In this article, we focus on the techniques that these MAC protocols apply to conserve energy. In addition, we also analyze and present the sources of energy utilization of these MAC protocols, which are summarized in a table in the appendix for the comparison. Moreover, we further analyze the advantages and disadvantages of each MAC protocols, so as to help researchers to easily understand the strengths and weaknesses of each protocol.

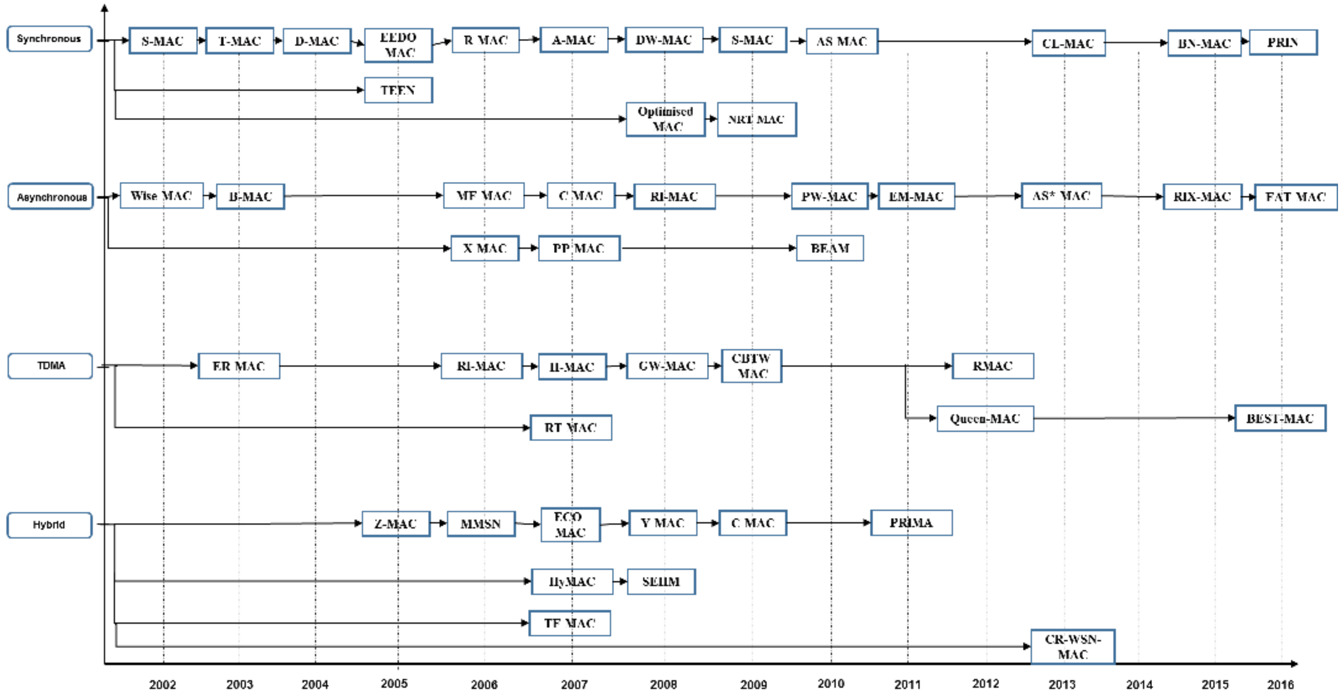


FIGURE 2. Taxonomy of WSN MAC protocols.

The remainder of this survey is organized as follows: Sections II introduces the standardized MAC protocol for IoTs and five main MAC behavior defined to support various IoTs applications with the diverse requirement. Section III presents the main attributes of MAC protocols for WSNs and introduces sources of energy waste. In addition, it also discusses different categories of MAC protocols for WSNs. Section IV, V, VI and VII introduce a number of MAC protocols under each category of MAC protocols for WSNs, in terms of their design, advantages, and disadvantages. Section VIII summarizes the survey the paper and finally, section IX presents the open research issues.

II. MAC FOR IoTs APPLICATION

Internet of things (IoTs) technologies have been developed towards ubiquitous communications for tremendous intelligent devices. IoTs applications have proliferated into both industries and peoples' daily life [36]. However, intelligent devices of IoTs applications are mostly energy constraint devices and needs to process complex computation. Therefore, energy conservation has been one of the primary design considerations for IoT applications and active research domain in recent years [36]–[38]. The rise of widely deployed IoT application has driven the research effort and standardization process. Because wireless connectivity of smart devices and wireless sensor nodes have similar characteristic in the networking and medium access protocols, protocols design for IoT can leverage on the experiences from existing energy-efficient MAC protocol of WSNs.

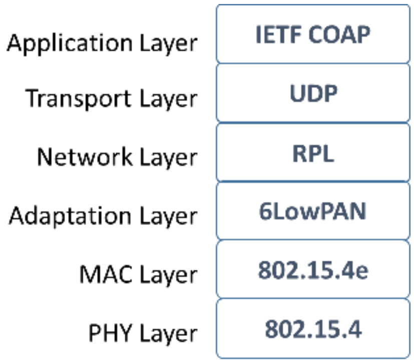
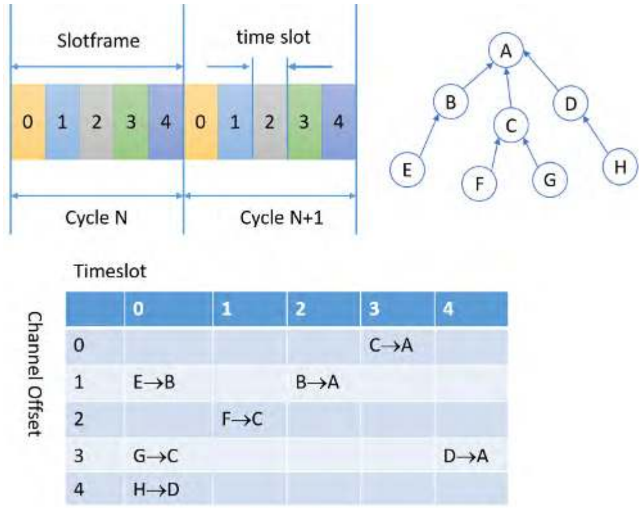


FIGURE 3. Standardized protocol stacks for IoT.

Figure 3 shows the standardized protocol stacks for IoT defined by IEEE and IETF [6], [39]. With the goal to support the emerging needs for seamless communication of embedded devices for IoT applications, IEEE defined 802.15.4e MAC protocol as an enhancement to address the limitation of 802.15.4 MAC protocol, in terms of delay, reliability and energy-consumption, etc [40], [41]. One of the key features of 802.15.4e MAC protocol is the design of extremely low-power consumption, with low duty cycle, dedicated slotted access, multi-channel communications, frequency-hopping as well as CSMA-CA [42]. As many IoT applications have low reporting frequency, such as smart meters, 802.15.4e MAC allows extremely low duty-cycle, i.e., 1% or even below. In addition, due to the wide range of IoT applications, one important requirement for MAC protocol design for IoT is the ability to support diverse objectives of functions. Specifically, there are five new behaviours modes defined by IEEE 802.15.4e MAC [42], to support different types of IoT applications, ranging from industrial and home automation application, remote monitoring and control, identification and tracking etc. The five modes are 1) time-slotted channel hopping (TSCH), 2) deterministic and synchronous multi-channel extension (DSME), 3) low latency deterministic network (LLDN), 4) asynchronous multi-channel adaptation (AMCA), 5) Radio Frequency Identification Blink (BLINK) [41].



	0	1	2	3	4
0				C→A	
1	E→B		B→A		
2		F→C			
3	G→C				D→A
4	H→D				

FIGURE 4. TSCH slot frame, and a sample tree-topology network with a possible link schedule for data collection.

TSCH can support various scenarios, ranging from process control to industry/home automation, with active research effort on enhancing the performance of TSCH [43]–[45]. TSCH is supported with enhanced beacons with time slotted access and has the capability of multi-channel and channel hopping. Figure 4 shows the slot frame structure that has five slots and a sample tree-structure of the network. As shown in the table, each node can transmit to its recipient at the assigned time slot and channel. Specifically, if two nodes are scheduled with the same channel offset and timeslot, a random back-off will be applied for nodes to access channel.

DSME is designed to support QoS-critical services, e.g., applications require highly reliable and scalable features, low latency. DSME uses a multi-superframe structure and a Contention Access Period (CAP) and a Contention Free Period (CFP), as shown in Figure 5. The number of a superframe in one MultiSuper frame is configurable by the coordinator. An enhanced beacon is used for the coordination of transmission, and the enhanced beacon is transmitted in CAP.

LLND defined the MAC behaviour for IoTs applications that operate in the harsh environment. Energy-constraint nodes interconnected by wireless links with dynamic and lossy wireless link conditions, resulting from channel fading, interference, or dust/heat/ moisture physical environment, are categorized by Low-power and Lossy Network (LLNs) [36]. A low latency superframes are used by the LLN coordinator, which includes beacons, timeslots for uplink, management and bidirectional timeslots [46]. LLND supports different mode of operations. Specifically, there are group acknowledgement (ACK) and dedicated ACKs upon successful reception of data packets.

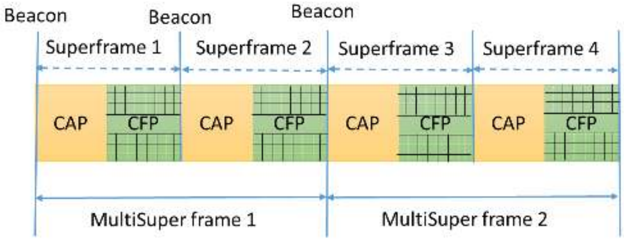


FIGURE 5. The multi-super-frame structure of DSME.

AMAC is used to support large-scale deployment network, such as smart utility networks, remote monitoring, etc. The asymmetry of wireless links is taken into consideration in AMAC, which relies on multi-channel capability. Each node can choose a channel that provides the best link quality. Besides, nodes use the beacon to update their neighbours about the listening channel that is selected.

BLINK is designed for identification purpose. BLINK allows the transmission of ID to other devices without requiring the association and ACK. Specifically, Aloha protocol is used by BLINK for channel access.

The huge potential and great convenience brought by IoT applications have attracted significant research attention, and energy efficiency is one of the key research issues for IoT [36]–[40]. Because wireless connectivity of smart devices and wireless sensor nodes have similar characteristic in the networking and medium access protocols, protocols design for IoT can leverage on the experiences from existing energy-efficient MAC protocol of WSNs.

III. PROPERTIES of MAC PROTOCOL FOR SENSOR NETWORK

A. ATTRIBUTES OF MAC PROTOCOLS

Energy efficiency is the most important attribute of MAC protocols for sensor networks. With the limited volume of energy storage, sensor nodes are required to function for a very long time. MAC protocols achieve energy efficiency by turning off the radio when the node is not transmitting or receiving. An ideal energy-efficient node would be one that sleeps most of the time and wakes up just to transmit or receive user data without any overheads. Energy efficiency directly influences network lifetime. *Scalability* and *adaptability* refer to the ability to accommodate changes in network size, node density, and topology. These changes can be attributed to mobility and failure of nodes. *End-to-end latency* refers to the delay from when a sender has a packet to send to the time it is received by the final receiver. *Throughput* refers to the amount of data that is successfully received by a receiver from a sender. *Fairness*refers to the ability of different nodes to share the network resources equally. *Channel utilization* reflects how well the entire bandwidth of the channel is utilized in communications [10], [47].

B. SOURCES OF ENERGY INEFFICIENCY

Energy is wasted when a radio is active while it is actually not doing anything useful or doing something redundant. As an example suppose two nodes A and B are communicating with each other where node A is a sender and node B is a receiver node. After a certain period of time node B assumes that the transmission from node A is finished and it goes to sleep mode. While node A has not finished with the data transmission and still has data packets for node B. In this case, energy wastage will occur as the node A will keep transmitting while the node B is in sleep mode. These activities of radio's are redundant when nothing useful is done and energy is simply wasted. There are a few sources of energy wastage that may be attributed to the MAC protocol scheme.

The collision causes corruption in data transmission and therefore the corrupted packets need to be discarded. These packets need to be re-transmitted, consuming energy and may cause another round of collisions. Collision increases latency as well. *Idle listening* refers to listening to a channel without actually receiving data. This happens when the radio is awake just listening to an idle channel. *Overhearing* refers to nodes receiving packets that are intended for other nodes. *Energy outspending* refers to due to lack of definition of transmission-reception power level according to topology specific criteria, affects badly power consumption, for example, the transmitter transmitting at the maximum power level. In addition to the increase in energy consumption, transmitting at high power also increases the level of interference at the transmission frequency, which may be currently used by other nodes. *Over-emitting*refers to transmitting packets while the destination node is not ready. *Control packet overhead* refers to sending and receiving packets which do not actually contain any data to be conveyed [47], [48].

C. CATEGORIES OF MAC PROTOCOLS

MAC-protocols can be categorized into two main categories: *contention-based* and *scheduled-based*.

In *contention-based* protocols, nodes need to compete for the shared wireless medium. Sensor nodes wait for a certain backoff period and perform a kind of channel sensing mechanism to check if the channel is currently busy before they actually transmit data. An advantage of contention-based protocols is that they are fairly simple compared to scheduled protocols, i.e. they do not require centralized control and fine-grained time synchronization. They are more scalable across changes in node density and traffic load. They are also more flexible for topology changes. The disadvantage of contention-based protocols is their inefficient use of energy mainly due to its mechanism. In high-traffic networks, many collisions may occur and thus it is difficult to determine throughput or maximum transmission delay. When control packets are necessary to avoid a collision, they can cause considerable overhead in sensor networks having small data packets.

There are two common methods of contention-based MAC protocols for WSN: synchronous and asynchronous protocols.

Synchronous protocols employ some kind of scheduling or synchronization between the nodes such that nodes are aware whether other nodes are active or sleeping. With that information, nodes can decide when to be awakened to listen for packets or to sleep to reduce overhearing or idle-listening. Synchronization messages may add up to overheads when they are not managed efficiently and are used only when needed. Frequent synchronization causes network overload with synchronization messages while infrequent synchronization may reduce the adaptability of networks to the mobility of nodes.

Asynchronous protocols do not require scheduling/synchronization between nodes. One of the methods is to employ *low power listening*(LPL) [49], or *preamble sampling*, [19], [50] that is, to let the receiver sleep most of the time and wake up shortly for a time interval to sense the channel for any *preamble* or RF layer signal to notify the receiver of incoming data being transmitted. When a sender has data, it will transmit a preamble during the sleeping period of a receiver. When the receiver wakes up, it detects the preamble and stays awake until the data is received completely. The advantage of asynchronous protocols is that there is no explicit synchronization between sender and receiver; therefore there is no synchronization overhead. Idle listening of the receiver is reduced. It is more flexible to topology changes. However, a longer preamble in low power listening suffers from several disadvantages: excess energy consumption in non-intended receivers due to overhearing of a long preamble, over-emitting of transmitters prior to sending the data, increase of latency at each hop, especially when the receiver wakes up at the beginning of the preamble. It also does not deal with collision. Some solutions are a) usage of shortened preamble length, b) receiver acknowledging transmitter to stop the preamble and start data transmission immediately, c) inclusion of the receiver address in the preambles and others.

In *scheduled* protocols, the nodes access to network resources, such as time and frequency, are scheduled among the nodes to prevent collisions. Slot scheduling also avoids energy losses due to idle listening and message overhearing by simply letting a node sleep when it is not using its slot. Control overhead results in energy inefficiency, due to the energy consumed in setting up and scheduling maintenance. However, since the mobility of sensor nodes is low, it does not require frequent scheduling adjustment, so that the overhead becomes negligible with the consideration of the long lifetime of sensor nodes. It is often needed to have a centralized base station that performs the scheduling assignment algorithm for the nodes to find a collision-free schedule. It is more suitable for networks where nodes are less mobile, and topology changes are not frequent.

In *TDMA-based* protocols, a single frequency channel is divided into time slots where each node is allocated a single transmission slot, hence this protocol is collision free [51]. TDMA needs tight clock synchronization to make sure that the time slots of nodes do not overlap each other. It may require frequent message exchange for this. When the channel contention is low, TDMA suffers from higher delays and lower channel utilization than CSMA, since TDMA only allows a node to transmit during the time slots that are scheduled to the node, but CSMA does not limit the transmission time of a node except for channel contention.

In *FDMA-based* protocols, available frequency bandwidth is divided into several frequencies or sub-bands. To prevent a collision, ideally, each node is assigned a unique physical frequency, based on some frequency assignment algorithm. The FDMA-based protocol requires more costly hardware, supporting multiple frequencies.

OFDMA is a multi-user version of the popular orthogonal frequency-division multiplexing OFDM digital modulation scheme. OFDMA splits radio signal into several smaller sub-signals first, then those sub-signals are sent out simultaneously with different frequencies. OFDM reduces the amount of crosstalk in signal transmissions. OFDMA is being considered for use by the fourth-generation wireless networks. The disadvantage of OFDMA is the complex OFDM electronics, i.e., the FFT algorithm and forward error correction result in inefficiency from the power consumption point of view. Because the OFDM electronics are constantly independent of the data rate, and data packets are combined for scheduling, which allows FFT algorithm to hibernate for certain time durations. Also, it is more complex to deal with co-channel interference caused by nearby cells in OFDM than that in CDMA. Therefore, dynamic channel allocation with advanced coordination is required among nearby base stations.

In some hybrid MAC protocols for WSNs, FDMA is combined with TDMA and some contention-based protocols, where time is divided into two periods: contention and scheduling periods. Contention period is normally used for broadcast, using a common broadcast frequency, and in this period, nodes need to gain access to the channel based on some contention mechanism. Unicast is done during the contention-free period according to the schedule of the individual nodes assigned by the base station or based on some distributed or random scheduling algorithm.

The main advantage of integrating FDMA into the protocol is to increase data throughput as more than one node can transmit and receive at the same time using different frequencies. Other techniques with multiple frequencies are frequency hopping, where a node switches to a different frequency if the channel is busy or contention occurs.

IV. SYNCHRONOUS-CONTENTION-BASED PROTOCOL

A. SENSOR MAC

Sensor MAC or S-MAC [52] is one of the original MAC protocols for WSNs, which is based on a synchronous duty-cycled protocol. Energy efficiency is achieved by having a period duty cycle, by which a node will switch between active and sleeping periods during its lifetime. The duty cycle and duration of active and sleep periods are fixed throughout the lifetime, depending on the application requirement. Duty cycling in S-MAC is shown in Figure 6.

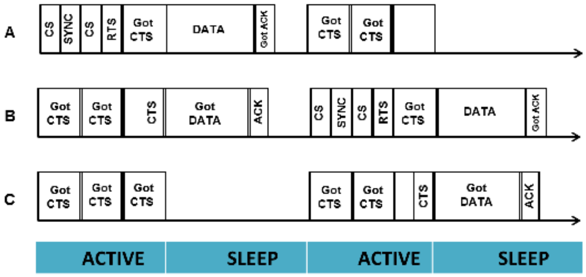


FIGURE 6. An example of duty-cycling in S-MAC, and data transmission from node A to node B followed by from node B to node C.

In the SYNC period, a node waits for or broadcasts a SYNC packet, a short packet that contains the node's address and the node's next sleep time. Synchronization is done periodically to reduce clock drift among neighbouring nodes. Neighbouring nodes with the same schedules form a *virtual cluster*.

S-MAC uses RTS/CTS handshaking mechanisms for data transmission to avoid a collision, overhearing and hidden terminal problems [53], [54]. It also uses a network allocation vector (NAV), which records the transmission period for virtual carrier sense. A node which wants to send a packet transmits RTS to the destination node. Since the RTS packet contains the destination address, other nodes know that they may sleep during the SLEEP period.

Advantages: S-MAC contributes a few important concepts such as message passing: long messages are divided into fragments and sent in a burst, using one RTS packet and one CTS packet to reserve the medium for transmitting all the fragments and ACK for each fragment. However, this is not good in terms of node fairness.

Disadvantages: Periodic sleep may result in high end-to-end latency, especially for multi-hop networks. The latency is because a node needs to wait until the next-hop node is awake before they can transmit. This is called *sleep delay*. Nodes at the boundary of two schedules have to adopt both schedules. So, the boundary nodes will consume more energy. In [55], Ye *et al.* introduced *adaptive listening*(S-MAC/AL) to reduce the end-to-end latency. Adaptive listening basically is to let other nodes that hear neighbouring transmissions of RTS/CTS packets to wake up in a short period at the end of the transmission. If one of these nodes is the next-hop path, it will be able to immediately receive the data, without waiting until the next listening period. Nodes that do not receive anything during the adaptive listening will go back to sleep until their scheduled listening period. The problem with adaptive listening is that nodes other than the actual next-hop node suffer from increased overhearing. Fixed duration of active and sleep periods in S-MAC decreases the efficiency of this protocol under variable traffic loads. While there is no traffic/data to transmit, idle listening occurs. High collisions may occur during broadcast between nodes in a virtual cluster due to their same schedule.

B. TIMEOUT MAC

Timeout-MAC or T-MAC [56] is derived from the S-MAC protocol wherein T-MAC, active and sleep periods are dynamically adjusted based on node activity and timeout. In T-MAC, a node remains active, that is listening or potentially listening, as long as it is in an active period. The active period ends if there is no activation event after a timeout period (TA). Activation events include the *firing of the frame timer or any radio activity*, including receiving or transmitting, *the sensing of radio communication*, or *the knowledge of a neighbouring sensor's data exchange*. The timeout period in T-MAC is set to be more than the length of C+R+T, where C is the length of the contention period, R is the length of an RTS packet and T is the turn-around time. Minimally, the timeout should allow nodes to hear the beginning of CTS packet. Data transmission between nodes is shown in Figure 7.

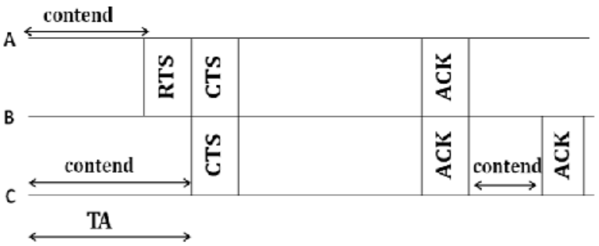


FIGURE 7. **DATA exchange between nodes A, B and C. Node C can overhear the CTS from node B, and it does not affect the transmission between Node A and Node B. TA for C need to be long enough so that it can receive the beginning phase of the CTS.**

T-MAC transmits the queued messages in a burst at the start of the frame. Because of this, the medium is saturated and it will wait for a fixed contention interval, even if no collision has occurred.

Advantages: Due to its dynamic timeout period, T-MAC consumes less energy over S-MAC in terms of reducing the idle listening problem. T-MAC is more adaptable to network load than S-MAC.

Disadvantages: Although T-MAC performs better in two-hop latency, the source node loses synchronization with the third-hop nodes and other nodes in the virtual cluster because the nodes do not hear communication from the source node to its two-hop nodes and subsequently go to sleep after a timeout. This is referred to as an *early sleeping problem*. The authors in [57] proposed two mechanisms to solve the problem: using future request-to-send (FRTS) packet and full-buffer priority. Another disadvantage of T-MAC is that many of the nodes in the interference range of sender or receiver will remain unnecessarily active. Nodes outside the interference range will still follow the basic periodic duty cycle and encounter the same problem as in S-MAC.

C. D-MAC

The data delivery path in WSN consisting of multiple sensor nodes and one sink is unidirectional from sensor nodes to the sink node, constructing a tree structure called, a data gathering tree. In D-MAC [58], the wake-up/sleep schedule of the sensor nodes is staggered according to the depth of the nodes in the tree, to allow continuous packet forwarding. Data gathering tree is shown in Figure 8.

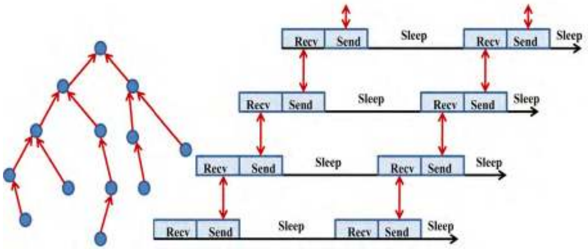


FIGURE 8. **D-MAC in a data gathering tree.**

The authors pointed out the common problem in protocols such as S-MAC and T-MAC: not all nodes beyond one hop away from the receiver can overhear the data communication, and therefore packet forwarding stops after a few hops. This is referred to as the *data forwarding interruption problem.*

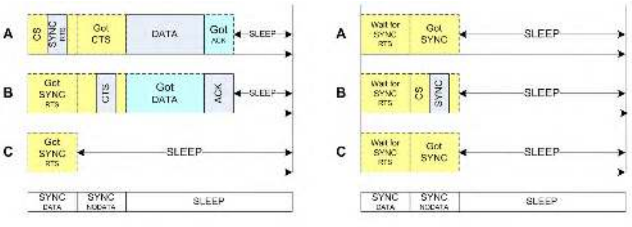
One cycle in D-MAC is in the order of RX (Receive), TX (Send) and a SLEEP period. In RX period, a node is expecting to receive a packet and send ACK to the sender. In the TX period, a node transmits a packet and then expects an ACK packet from the receiver. In the SLEEP period, the node switches off its radio to save power. Both RX and TX period length is u, followed by a long SLEEP period. A node at depth d in the data gathering tree starts receiving at $u*d$ ahead of schedule of the sink. Data gathering is only unidirectional from sensor nodes to the sink. When there are multiple packets to transmit in a TX period, a node needs to increase its duty cycle and request nodes along the multipath to increase their duty cycle as well.

Advantages: Reduced end-to-end latency from sensor nodes to sink. Energy is conserved because the node goes to SLEEP mode immediately after receiving an ACK packet from the receiver. In the context of sensor networks with the small data packet, this Protocol avoids the overhead caused by RTS/CTS by using an ACK after data transmission.

DisAdvantages: Collision at the same node level. Creating and maintaining data gathering tree also causes a concern for energy consumption. D-MAC is more suitable in networks with low nodes mobility in order to have a stable and reliable data gathering tree for a considerable length of time. It is also limited to unidirectional traffic from multiple sensor nodes to sink node. Performance evaluation of D-MAC shows that D-MAC outperforms S-MAC in terms of end-to-end latency. D-MAC also consumes less energy compared to S-MAC. However, throughputs for D-MAC and S-MAC are comparable.

D. TEEM (TRAFFIC AWARE ENERGY-EFFICIENT MAC)

Although S-MAC [52] can reduce idle listening time, it is not optimal due to a fixed active period. The author pointed out that while no nodes have data traffic to send during some time frames, no RTS/CTS packet may occur in the corresponding listen period. However, in S-MAC, the node still has to be awake, i.e. idle listening. This is because S-MAC, T-MAC [56], D-MAC [58] etc do not consider actual traffic information in the network. The authors of TEEM [59] proposed modification over S-MAC and similar protocols, e.g. T-MAC and D-MAC, with the intention to reduce idle listening when there is no data transmission by turning off the node's radio much earlier. Working of TEEM is shown in Figure 9.



(a) (b)

FIGURE 9. **TEEM reduces the use of control packets, overhearing, and idle listening.**

In TEEM, the active period is divided into two parts: $\text{SYNC}_{\text{DATA}}$ period and $\text{SYNC}_{\text{NODATA}}$ period. A node with data to transmit will contend for the channel and transmit a SYNC_{RTS} packet in $\text{SYNC}_{\text{DATA}}$ period. SYNC_{RTS} is a combination of SYNC and RTS. The thought behind this is a node with data to transmit can transmit its schedule together with RTS packet, and therefore it only needs to contend the channel once. Destination node, after receiving a SYNC_{RTS}, immediately sends a CTS packet to the sender and data transmission will commence during the SLEEP period. Other nodes receiving SYNC_{RTS} knows that the incoming data is not destined for them, putting itself to sleep immediately to avoid overhearing during $\text{SYNC}_{\text{NODATA}}$ period. When there is no data to transmit, the node transmits a SYNC packet only during $\text{SYNC}_{\text{NODATA}}$ period for synchronization purpose.

Advantages: Energy efficiency is increased as compared to S-Mac and TEEM as a result of reduced listen period. The number of control packet transmission is reduced.

DisAdvantages: Although energy consumption is lower due to a reduction in usage of control packets and overhearing, it still suffers from high end-to-end delay latency because of its fixed periodic duty cycle.

E. ENERGY EFFICIENT AND DELAY OPTIMISED MAC

The EEDO-MAC [60] protocol uses carrier sensing of control packets, i.e. RTS and CTS to reduce the end-to-end delay in multi-hop data transmission. The main aim of this protocol is to reduce the end-to-end delay of data packets, making it useful for delay sensitive applications. This protocol is based on the fact that nodes within the carrier sensing range are able to sense that transmission has occurred, but they are not able to decode the data content. Nodes in carrier-sensing range are potential nodes to be the next-hop node after the one-hop neighbours of the current sender. Carrier sensing range is typically two times the transmission range, i.e. distance of one-hop neighbours [61]. The proposed scheme is simply to increase the duty cycle of nodes within the carrier sensing range so that they can wake up more often to receive and forward the data. Figure 10 shows how nodes in A's carrier-sensing range increase their duty cycle.

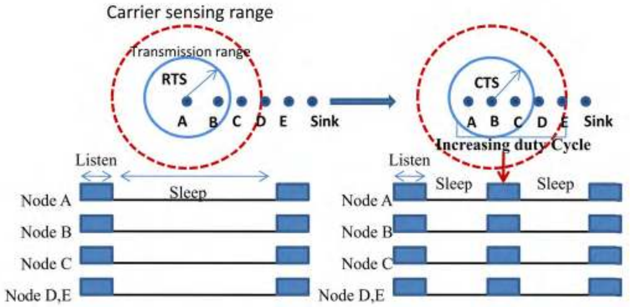


FIGURE 10. **Nodes in A's carrier-sensing range increase their duty cycle.**

Advantages: End to end delay of data packets is reduced to a significant amount as compared to S-MAC [52] and Adaptive S-MAC. The protocol is most suited for applications where a small delay is potentially serious, such as military and healthcare areas.

DisAdvantages: Although increasing duty cycle reduces end-to-end delay, nodes within the carrier-sensing range, including those that are not part of the multi-path, experience increase in idle listening and overhearing.

Simulation results of EEDO-MAC perform better in terms of energy-delay-cost per bytes compared to SMAC and SMAC/AL.

F. ROUTING-ENHANCED MAC

The design goal of Routing-Enhanced MAC [62] or R-MAC is to forward data multi-hops within a single operational cycle. Nodes along the data forwarding path need to be awake only when they are transmitting or receiving data.

When a node has a data packet to transmit, instead of using RTS/CTS mechanism, it transmits PION (Pioneer frame) control packet in the DATA period, where all nodes need to be active. A PION contains current node address, next-hop address, previous-hop address, and duration of the transmission. As an RTS, PION is used to request communication. PION packet is also used to confirm communication, like a CTS packet. For example, from the point of view of the node A to node S: PION packet serves as a confirmation (CTS), to node B, it serves as a transmission request (RTS).

During the SLEEP period, each node that sent or relayed a PION needs to be awake only at some specific time to

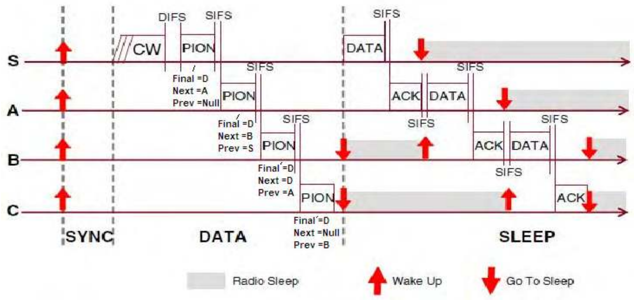


FIGURE 11. R-MAC overview and PION transmission.

transmit or forward the data packets. Based on the formula:

$$T_{Wakeup}(i) = (i-1) * (durDATA + SIFS + durACK + SIFS)$$

A single data frame is sent during the time period of durDATA, and an ACK is sent during the time period of durACK. SIFS is short interframe space which differs the communication for a short period of time. Network Allocation Vector (NAV) in R-MAC records segments of time instead of a single duration. A node receiving the packet must return an ACK packet to the sending node, which after receiving the ACK packet will immediately go to sleep again.

Advantages: Protocol is able to forward a data packet to multiple hops in a single operation cycle due to this end to end delay is reduced significantly. R-MAC can make use of contention window time to transmit more PION control package in one data period. R-MAC is more energy efficient than S-MAC due to the overall reduction of control packets in the DATA period. Its traffic contention handling is better than S-MAC, without sacrificing energy efficiency or network throughput.

DisAdvantages: Even though overhearing is reduced in SLEEP period, it still exists during DATA period. R-MAC do not support broadcast and burst data mode. Two hidden source nodes which have succeeded in scheduling through PION can cause collisions at the beginning of the next sleep period.

G. ADAPTIVE MAC

The design goal of Adaptive MAC [63] or A-MAC is to guarantee the pre-configured network lifetime and to reduce end-to-end latency. It is a similar protocol to S-MAC, but the listen/sleep duty cycle is adjusted according to the *remaining energy* of each node. A node with relatively higher remaining energy wakes up more frequently and serves more for the network. Data traffic load over the network lifetime will be distributed almost equally between each node, resulting in the fairness of each node's energy consumption rate. Sensing coverage that relies on the number of remaining active sensor nodes is improved.

The duty cycle of each node is adjusted according to the difference between preconfigured network lifetime and elapsed lifetime ratio, and current energy consumption rate of the node. This difference can be calculated by:

$$\delta = \frac{T_{elap}}{T_{conf}} - \frac{E_{cons}}{E_{init}}$$

Where, T_{conf} and T_{elap} represent the pre-configured network lifetime and the elapsed lifetime, respectively. E_{cons} and E_{init} represent the dissipated and initial energy of a node, respectively. A simple data transmission between the nodes having a different duty cycle is shown in figure 12.

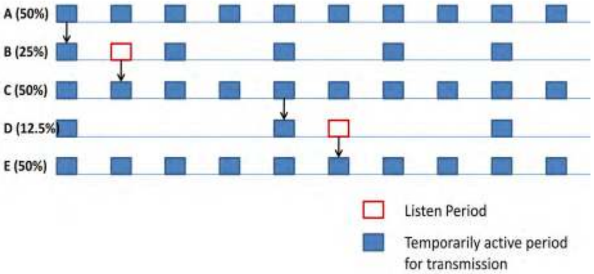


FIGURE 12. Data transmission from node A to node E.

The duty cycle is adjusted if the difference is greater than or less than certain upper or lower threshold respectively. The duty cycle is increased or decreased by a factor of two to make sure that the node with higher duty cycle is still in sync with nodes with a lower duty cycle. The new schedule is broadcast using SYNC packet and it is only transmitted every n listen/sleep cycle of the minimum duty-cycle to reduce too frequent broadcast collision. To avoid the periodic route discovery, sink triggered route discovery is implemented if it is found that the average duty cycle value of the received packet is below a threshold.

To further improve A-MAC's goal to improve network lifetime, it is suggested to use routing protocols that make use of energy consumption data in deciding routing path. Two routing metrics, Max-min and Max-avg, is proposed to properly utilize the potential of A-MAC. In performance evaluation, A-MAC shows that it prevents network partition or sense holes occurrence until the pre-configured lifetime, regardless of the network traffic load. The end-to-end latency of S-MAC is mostly dependent on the duty cycle, whereas, in A-MAC, latency is lower as traffic load is less.

Advantages: A-MAC does not require complex configuration of the duty cycle of each node. It uses sink triggered route discovery for new routes reducing the unnecessary control overhead.

DisAdvantages: A routing protocol considering the remaining energy of the node is required to get the best performance of A-MAC. Delay increases, when event occurrence rate increase in A-MAC has to fulfil its predefined network lifetime, reducing the duty cycle of the nodes.

H. OPTIMIZED MAC

The basic concept of Optimized MAC [64] is to set a duty cycle based on the traffic load. Network load is based on the pending messages in a queue of the particular sensor node. This protocol adopted the synchronization process of S-MAC, using the same SYNC packet. However, data and control packets are modified such that SYNC and RTS are combined into SYNC_{RTS} to reduce packets overhead and further reduction of energy consumption and latency.

Each sensor keeps track of the traffic load based on the number of messages in its queue. Each time after receiving a packet node increases it packet counter to keep track of a number of the packet in its queue. If the number of messages exceeds a certain threshold, this node transmits SYNC_{RTS} that contains its increased duty cycle. The nodes receiving SYNC_{RTS} adjust its duty cycle accordingly.

Advantages: Consider the traffic load to adjust the duty cycle.

DisAdvantages: Topology taken for simulation is not good to give the standard result. One node with more data will cause his neighbors to increase their respective duty cycle, which will increase the energy consumption and idle listening.

I. DEMAND WAKEUP MAC

Demand Wakeup MAC [65] or DW-MAC is a synchronized duty cycle protocol. Every cycle is one SYNC period, DATA period and a SLEEP period. DW-MAC wakes up a node when there is a demand for data transmission and reception. The adaptive wakeup on demand can increase the efficiency of channel capacity when traffic load increases, so that it can achieve low end-to-end latency under various traffic loads for unicast or broadcast traffic.

In DATA period, a node with data to transmit sends an SCH (scheduling) frame to the receiver node. There is a one-to-one mapping between DATA period and a SLEEP period. The interval time (T_1) from the start of DATA period until the starting time of transmission of SCH is proportional to the interval (T_2) of the start of SLEEP period until the time when the node needs to wake up again during the SLEEP period (On Demand Wakeup). The time duration (T_3) of the SCH frame is proportional to the interval time (T_4) of on-demand wakeup time. T_1 sets up the delayed transmission of a DATA packet during the SLEEP period.

Scheduling frame (SCH) replaces the RTS/CTS frame. It contains a destination address so that SCH only wakes-up the intended receiver. SCH also contains cross-layer information such as source network layer address for broadcast packets and destination network layer address for unicast packets. It supports scheduling setup for a node between its next hop neighbor nodes even before the reception of data packets.

For broadcast transmission, the sender node transmits SCH and DATA. For unicast transmission, after sender node transmits SCH, receiver replies with another SCH as a confirmation to the sender. Similar to PION in R-MAC, this SCH is also used to set up the transmission to the next node.

Advantages: DW-MAC avoids the Data packet collisions at their intended receiver. The use of the SCH frame helps the DW-MAC to avoid possible collisions between two hidden sender nodes.

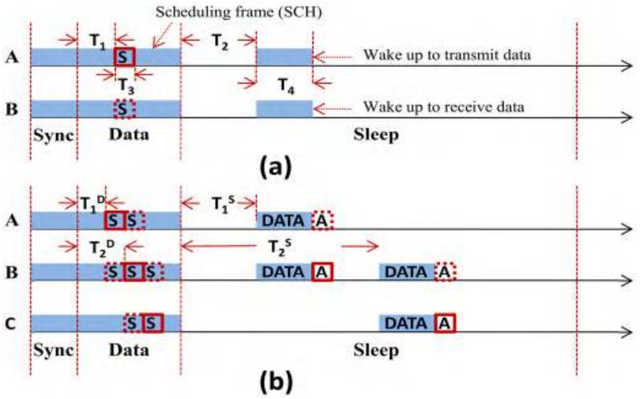


FIGURE 13. (a) Overview of DW-MAC. (b) Optimized forwarding of a unicast packet.

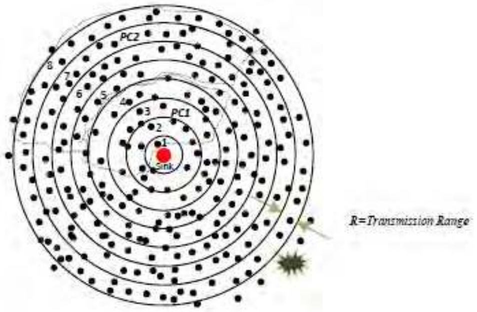


FIGURE 14. An example of a network division in W-MAC [66].

DisAdvantages: DW-MAC does not support the variable data packet and burst mode.

J. WAVE-MAC

Wave-MAC [66] or W-MAC is a synchronous duty-cycled, contention-based protocol. W-MAC is designed for the event-driven and delay sensitive application in large-scale WSNs.

W-MAC assumed that the sink is placed in the center of the network. It uses the S-MAC synchronization technique with some modification (*SyncTag* is added in the synchronous packet). An algorithm is proposed to perform the local and global synchronization. It utilizes the Future RTS (FRTS) feature used in T-MAC. It assumes the DATA flow as uni-directional from sensor nodes to sink. The network field is organised by the concentric circles around the sink. The difference between the two concentric circles is the transmission range of a node.

The synchronization in W-MAC leads to the formation of Path-cluster and Waves. P-Cluster is limited to three consequent hops and a Wave consist of several consecutive P-Clusters. The number of P-Clusters at each Wave is directly related to the size of the network.

W-MAC assumes that the location information of each node in the network and sink is known. Each node in the network is assigned a NodeTag. The packet is always forwarded from a node to the same or lower NodeTag node and only these nodes are able to adjust their timer to wake-up and receive data.

Advantages: End to end delay and energy conservation is improved because of control packet overhead reduction and limiting the wake-up of overhearing nodes to same and lower hops node. W-MAC performance in low as well as high traffic is comparable with the S-MAC.

DisAdvantages: However the network is divided into the cyclic concentric areas by utilizing the location information of nodes but this requires good localization algorithm to calculate the exact position of the nodes and big overhead in case of mobile nodes. In the case of heterogeneous transmission range, W-MAC will face several problems as one is dividing the network into concentric areas.

K. A NOVEL REAL-TIME MAC

A Novel Real-Time MAC [67] or NRT-MAC is based on the idea of contention based protocol S-MAC. However, NRT-MAC uses a feedback approach as the medium access strategy, whereas S-MAC is a contention-based protocol that uses back-off schemes.

The main aim of NRT-MAC is to be the best suited protocol for real-time wireless sensor networks, while several other real-time protocols like Virtual TDMA for Sensors (VTS), Implicit Earliest Deadline First (I-EDF), Path Oriented Real-time MAC (PR-MAC), Channel Reuse-based Smallest Latest-start-time First (CR-SLF) and TDMA based hard real-time MAC (RRMAC) are still into existence. Figure 15 shows the functioning of NRT-MAC.

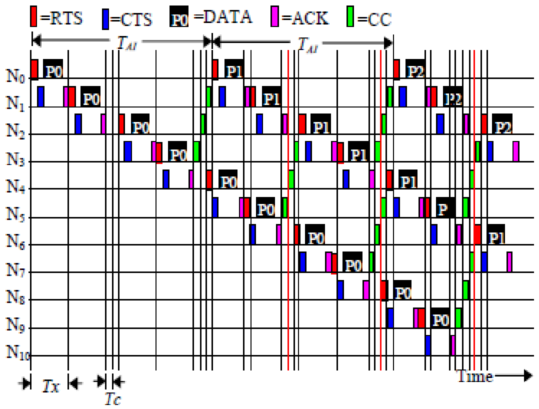


FIGURE 15. The timing diagram of packet transfer in NRT-MAC [67].

NRT-MAC uses RTS_CTS like the 802.11 and S-MAC to deal with the hidden terminal problem. It uses the feedback control packet called Clear Channel (CC) to remove the uncertainty of winning the channel among the several nodes wishing to send the data packet. This control packet CC is used to assign a Boolean value to Clear Channel Flag (CCF) and has a Clear Channel Counter (CCC) with an integer value range from 0 to 3. DATA transfer cycle duration is designated by T_x and the duration of one control packet is designated by T_c.

Advantages: Guaranteed lesser end-to-end delay and packet transfer delay for the soft real-time application. Contention and collision are less because of the feedback medium access strategy used in the protocol.

DisAdvantages: The delay is less in the NRT-MAC, but the control packet overhead is very high. The protocol only considers one source and one destination and is not scalable during the lifetime of the communication stream in randomly deployed WSNs.

L. AS-MAC

An Adaptive Scheduling MAC (AS-MAC) protocol [68] is proposed to make nodes' active duration adaptive to traffic load. Specifically, when the traffic load is high, AS-MAC can achieve rapid data dissemination and reduce transmission latency by scheduling more transmission. In addition, when the traffic load is light, nodes switch to a sleeping mode in a timely manner, such that idle listening is mitigated and energy conservation is achieved. Evolving from DW-MAC [65], AS-MAC also makes sensor nodes wake up on demand to transmit or receive data packets. However, different from DW-MAC, AS-MAC makes use of the AS period to replace the Data period, so that the active time can be adaptively changed.

AS-MAC introduces a flexible Reserved Active Time (RAT) within the AS period. The length of RAT has changed adaptively to variable traffic load. A timer is designed for a node to determine the necessity of entering sleep mode. Figure 16 shows that in each operation cycle, the length of RAR is adaptively changed with a different number of events (traffic load).

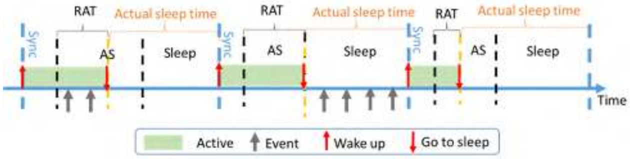


FIGURE 16. The reserved active time is adaptively changed in AS-MAC.

In addition, to solve the problem of delay of scheduled transmission and prevent duplicate packet transmission, AS-MAC introduces two new parameters in the SCH, i.e., RTS_RetryNo and CTS_RetryNo. With the help of these two parameters, whether or not the distinct SCH transmission is successful can be determined, so as to avoid duplicate packet transmission.

Advantages: Under high traffic load, AS-MAC allows more data transmission in one operational cycle, while the data transmission is resiliently scheduled in the sleep period. AS-MAC can achieve the goal of energy saving and reduction on latency by successfully mitigating the duplicated data transmission and idle listening, respectively.

DisAdvantages: In order to enhance the broadcast performance, AS-MAC prevents nodes at different locations from entering sleep mode early by adjusting the timeout duration. Specifically, the farther a sensor node locates away from the sink, the longer timeout duration that node needs to wait. Although this scheme can achieve shorter latency, more energy will be consumed, especially when the network size is large.

M. CL-MAC

A Cross-Layer MAC protocol (CL-MAC) [69] is proposed to support multi-flow and multi-hop packet transmission while reducing the latency, improving packet delivery ratio and conserving energy per packet transmission. CL-MAC takes into consideration the pending packets from the routing layer and the flow request from its neighbor nodes when it sets up a flow. CL-MAC establishes communication with the help of Flow Setup Packets (FSP). The length of FSP varies depending on the number of packets, flows, and receivers. The FSP works as RTS packet for the destination node and as CTS packet for the source node. When a node has packets for different destinations associated with different next-hop forwarders, it sends the FSP with the indication of the priority of next-hop forwarders. When nodes receive a FSP message, they reserve the time slot according to their priority indicated in that message. In addition, CL-MAC introduces Network Allocation Vector (NAV) for timeslot reservation, such that nodes closer to the destination have a longer waiting period. For the flow setup, CL-MAC enables a single node to transmit multiple flows over multiple hops within every frame.

Advantages: CL-MAC can effectively exploit the utilization of sleep period with the design of FSP. In a single wake-up cycle, a node can schedule multiple flows for multiple destinations through multi-hop data forwarding, which results in a significant reduction of latency and improvement of throughput.

DisAdvantages: The length of FSPs messages depends on several factors. With an increase in a number of flows, packets, and receivers, the length of the FSPs message also increases, which results in significant overhead. This overhead leads to increased energy consumption in the network.

N. BN-MAC

An energy-efficient, low-duty-cycle and mobility-based Boarder Node-MAC (BN-MAC) are proposed in [70] to achieve low latency, energy conservation, enhanced throughput with the capability to support mobility and scalability. In BN-MAC, the network is segmented into several regions. Each region contains one Border Node (BN), which relays data from nodes inside the region to outside that region. BN-MAC introduces the dynamic BN selection process (DBNSP) model to select BN according to residual energy, memory allocation resource, and signal strength.

There are three phases in BN-MAC protocol, i.e., topology setup phase, intra-semi-synchronized communication phase and inter-synchronized phase. During the topology setup phase, each node maintains two nodes among its one-hop neighbors, i.e., the principle node and the backup node. A node relies on its principle node for data forwarding. When the principle node is unavailable, a node uses it's the backup node to relay the packets. BN-MAC introduces intra-synchronized communication phase and inter-synchronized communication phase. During intra-semi-synchronized communication phase, a node chooses to synchronize with either the principal or the backup node by using a short preamble message. During the inter-synchronized communication phase, Border Nodes first send three HELLO messages to wake up neighbors, and then transmit Border Node Indication Signal (BNIS) to let neighbors understand its transmission schedule.

The idle listening in BN-MAC is eliminated by using the idle listening control (ILC) model. Specifically, in BN-MAC, nodes go to sleep mode once the timer timeout. This allows the nodes to conserve energy.

Advantages: BN-MAC utilizes a low duty cycle and introduces a semi-synchronization approach. Dynamic selection of BN improves the lifetime of the network significantly.

DisAdvantages: The selection of BN requires the exchange of control messages, resulting in additional energy consumption. The transmission in each region is under the control of a BN. Once the BN's energy drains out or it moves out of that region, all nodes inside a region suffer from communication failure.

O. PRIN

A QoS protocol, i.e., a priority-based energy-efficient MAC protocol, namely PRIN, is proposed for WSNs [71]. PRIN uses two kinds of priorities. Nodes that are closed to the source node are given high priority. The priority of nodes is decreasing towards the receiver. Furthermore, PRIN makes use of priority queues for data with different QoS requirements. In PRIN, the packet arrival is considered as three processes, i.e., inter-arrival process, retrial process, and services process, which are independent of each other.

Once an event occurs in the network, the classifier of a node identifies the priority of the data. If the size of a queue is MAX, the sample inter-arrival rate of data varies. In addition, retransmission is applied to provide reliable data delivery. When the data cannot be successfully delivered and the number of retransmission reaches the maximum limit, that data is discarded from the queue. In addition, to avoid packet collision, a back-off time is randomly chosen. Furthermore, successful transmission is acknowledged by ACK.

Advantages: PRIN can achieve high throughput with reduced latency by varying the inter-arrival rate.

DisAdvantages: Under interference, PRIN cannot achieve better throughput, compared to S-MAC [52] and T-MAC [72]. PRIN needs to be modified to reduce packet loss due to interference.

V. ASYNCHRONOUS-CONTENTION-BASED PROTOCOLS

A. WiseMAC

WiseMAC [73] is based on preamble sampling techniques and its main aim is to reduce the length of the wake-up preamble. If a node senses that the medium is busy, it continues to listen until it receives a data packet or until the medium becomes idle again.

Sampling schedules of the sensor nodes are made known to other sensor nodes in the ACK packet transmitted by the receiver at the end of data transmission. With this information, a sender will wake up just at the right time when the receiver gets active to sample the channel with a period of T_W. The preamble length (T_P) is adjusted dynamically based on

$$T_p = \min(4\theta L, T_w)$$

Here, θ is the frequency tolerance of the time-base quartz and L is the interval between the communications. This resulting WiseMAC has less overhearing in high traffic conditions.

During low traffic, the length of the preamble may exceed the data frame length (T_D). In this case, WiseMAC repeats the data frame with the extended preamble. Upon receiving the data frame, receivers process it to determine whether or not it is the intended recipient of this data frame, and it goes back to sleep if it is not the recipient. The node only remains awake if it is the intended recipient of this data frame, and it sends an ACK message at the end of the transmission. A simple data transmission between nodes is shown in Figure 17. It is shown that the sender wakes up just at the right time when the receiver gets active to sample the channel. The receiver sends an acknowledgement after receiving the data frame.

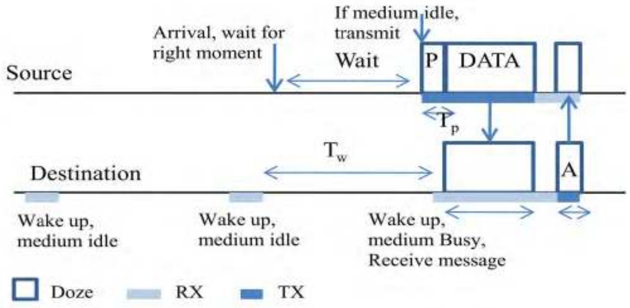


FIGURE 17. WiseMAC.

Advantages: WiseMAC can achieve better performance with its dynamic preamble length adjustment scheme for variable traffic load compared to S-MAC. Overhearing is reduced significantly when traffic is high.

DisAdvantages: For frequently changing topology, WiseMAC can cause high preamble overhead and high latency because some nodes have to use long preambles after failing to communicate with the destination.

B. BERKELEY MAC

Berkeley-MAC or B-MAC [74] uses low power listening (LPL) and extended preamble sampling techniques to achieve low power communication. In low power listening, a receiver node periodically wakes up for a short period to check any activity in the channel by using Clear Channel Assessment (CCA). If the receiver senses a preamble, it remains awake until the end of the preamble, which is immediately followed by the data.

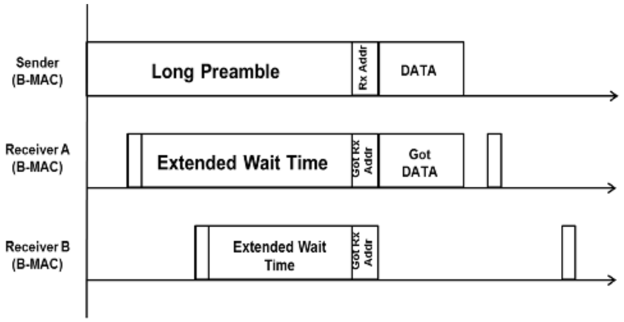


FIGURE 18. Low Power Listening in B-MAC.

A receiver node knows if the data is intended for it from the data header. It will continue receiving the data if the data is for it, or simply discard the data and go to sleep if the data is not for it. Preamble length is set to at least the receiver's wake up interval in order to reliably receive data. Figure 18 shows the low power listening in B-MAC. A long preamble is sent before the data packet. Receiver nodes A and B listens to the preamble first. Receiver node A receives the full data packet while node B discards the data packet as it is not intended for node B.

Advantages: Being just a link protocol, B-MAC is lightweight and configurable, and can be integrated with other protocols above it. Preamble length is also set by the upper layer to determine the optimal length.

DisAdvantages: Receiver's energy is wasted during the extended preamble since the only way to know if the data is intended for it is by waiting until the data header is received. Over-emitting also occurs at the transmitter due to the length of the continuous preamble. B-MAC does not provide multi-packet mechanisms like hidden terminal support, message fragmentation nor does it enforce a particular low power policy.

C. X-MAC

X-MAC [75] also uses preamble sampling techniques for low power communication. Its design goal is to address the *problems of overhearing*, *excessive preambles*, *packetizing radios*, and *lack of automated adaption to varying traffic load*.

Several short preamble packets carrying receivers ID are transmitted when the sender has data to send in contrast to using a long preamble in B-MAC [74]. If a node wakes up and receives a short preamble packet, it looks at the receiver node ID inside the packet. If the node is not the intended receiver, it returns to sleep and its duty cycle continues as normal, thus avoiding the overhearing problem. If the node is the intended recipient, it immediately transmits an ACK to the sender and remains awake for the subsequent data packet.

On the sender side, between the short preambles, the sender waits for an acknowledgement from the destination node. When an early acknowledgement is sent back to the sender, it stops sending the preambles and starts transmitting the data packet. These short preambles are referred to as strobe preambles, i.e. the sender quickly alternates between short preamble packet and a short wait time. Figure 19 shows the working of X-MAC with its strobed preambles. Receiver A sends the ACK to the sender as it is the intended receiver of the packet while receiver B goes to sleep after listening to the short preamble as it is not the intended receiver of the data packet. Receiver A receives the data packet while receiver B returns to its duty cycle.

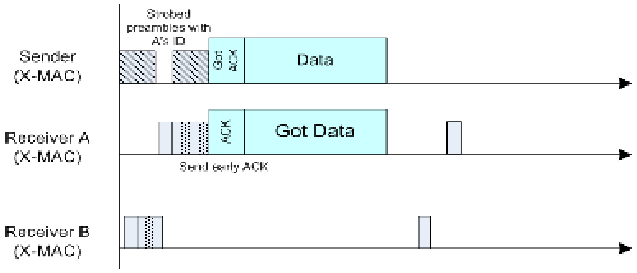


FIGURE 19. X-MAC with its strobed-preambles.

Advantages: X-MAC's algorithm adapts the duty cycle of the receiver automatically under varying traffic load. X-MAC does not have any radio limitation i.e, the short strobed preamble is well suited to all types of digital radios like Chipcon CC2420 [76], CC2500 [77] and MaxStream XBee [78]. X-MAC performs better in terms of energy-efficiency and latency compared to LPL due to its strobed preamble mechanism.

DisAdvantages: This protocol may not be suitable for broadcast communication and it may consume more energy to transmit broadcast packets to all intended nodes.

D. MICRO-FRAME PREAMBLE MAC

Micro Frame Preamble MAC [79] or MF-MAC is an asynchronous contention-based MAC protocol using preamble-sampling techniques where the continuous preamble is replaced by a series of small frames, called *micro-frames*. Each micro-frame contains information such as destination address and a hash of data field. The receiver can recognize if the incoming data is useful according to the information in the micro-frames.

The micro-frame contains the following field: type, destination address, sequence number and the hash value of the incoming data. Type field distinguishes data frames from acknowledgement frames. Based on the micro-frame sequence number, the receiver can estimate when the actual data will be transmitted. This means the receiver is allowed to sleep until the actual data is transmitted. To avoid listening to irrelevant data, the receiver reads the destination address field of the micro-frame and checks if the incoming data is intended for it. Each node keeps track of the hash value of the frames that the node has already sent or received. This is useful to check if the node has already received the same broadcast data forwarded by other nodes.

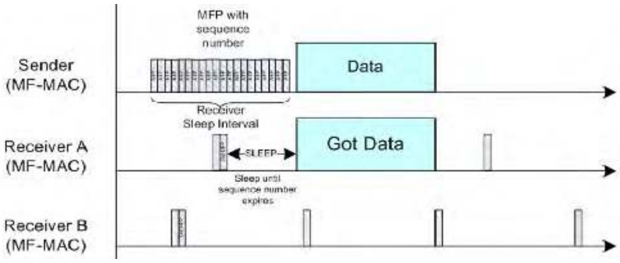


FIGURE 20. MF-MAC.

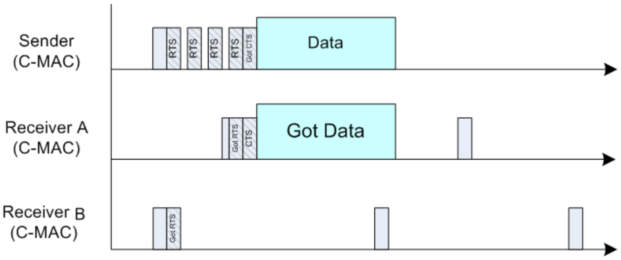


FIGURE 21. Aggressive RTS in C-MAC.

Advantages: MF-MAC reduces overhearing by letting the node to sleep after receiving a micro-frame. Keeping the hash data field in the micro-frame avoids receiving the same broadcasted data. Energy is saved by not receiving the irrelevant data packets.

DisAdvantages: However, since receiver still needs to wait until all the micro-frames are transmitted, it will suffer from high latency similar to LPL. Transmitter still suffers from over emitting since it keeps transmitting MFP.

E. CONVERGENT MAC

Sha *et al.* [80] highlighted the drawbacks of the long preamble mechanism used by MAC protocols such as B-MAC. Long preambles cause accumulation of latency along multi-hop routes, inefficient energy usage of the transmitter due to the need for transmitting the preamble long enough and overhearing problem on nodes other than the intended receiver. Other protocols that used periodic synchronization such as S-MAC, T-MAC and D-MAC consume significant energy even when no traffic is present.

The design goal of Convergent MAC [80] or C-MAC is to reduce energy consumption while maintaining reduced latency and high throughput. C-MAC uses unsynchronized sleep scheduling when there is no packet to transmit. For transmission, C-MAC uses three main components: *aggressive RTS with double channel assessment*, *anycast for quick forwarder discovery*, and *convergent packet forwarding for anycast overhead reduction.*

Aggressive RTS is a long preamble that is broken into multiple RTS packets or *RTS burst*. Short gaps in between these RTS packets are to allow the receiver to send back CTS packets to the transmitter. The transmitter, upon receiving CTS packet, can send the data immediately. For every certain interval, the receiver wakes up and senses the channel quickly *two* times or does *double channel check*. To avoid a collision, before transmitting the first RTS burst, the sender will assess the channel by using carrier sensing or by receiving RTS burst from other nodes during an RTS gap.

Anycast-based forwarding is basically to select the next node based on its distance to the destination node. When there are more than one-hop nodes listening to the same RTS bursts, the node closest to the destination nodes has higher priority to transmit CTS to the sender. The prioritization is based on certain routing metrics mentioned in the paper.

Convergent packet forwarding is introduced to reduce the overhead of anycast-based forwarding. If suddenly after the anycast-based forwarder has already been selected, a node with better routing metric awakes, C-MAC will use unicast instead of anycast.

C-MAC also features *synchronized wake-up* schedule to save more energy. During the convergence from anycast to unicast process, the sender synchronizes its schedule with the receiver. These nodes maintain the schedule between them as long as there is traffic. And after a certain timeout without traffic, the nodes go back to unsynchronized duty cycling.

Advantages: CMAC uses a low duty cycle and avoids any kind of synchronization while supporting low latency. Double channel check avoids the risk of missing the RTS burst.

DisAdvantages: CMAC uses low duty cycle but this can lead to longer duty cycle length because the time to check the channel is fixed. Using the RTS_CTS in unicast always causes overhead when compared to unicast and can end up with a suboptimal path if the best next hop is sleeping.

Based on simulation and experiment, C-MAC's throughput is much above S-MAC and GeRaf [81], [82]. C-MAC outperformed S-MAC in latency and energy efficiency.

F. PATTERNED PREAMBLE MAC (PP-MAC)

PP-MAC [83] is another preamble sampling protocol. Instead of using a long preamble like in B-MAC, it uses a short preamble. The preamble includes destination address in order for the nodes to decide if the incoming data is meant for it. After the preamble is transmitted, the sender switches to receive mode, waiting for an ACK from the intended receiver. The intended receiver, as soon as it knows that the incoming data is for it, transmits an ACK to the sender. Other receivers go to sleep. The sender transmits the patterned preamble for the same duration as the receiver's sleep period. Figure 22 shows the preamble and data transfer between the nodes in PP-MAC. Receiver A sends an ACK as the data packet is intended for it while the receiver B goes to sleep.

Advantages: Claims to be more efficient in terms of channel utilization and delay than B-MAC.

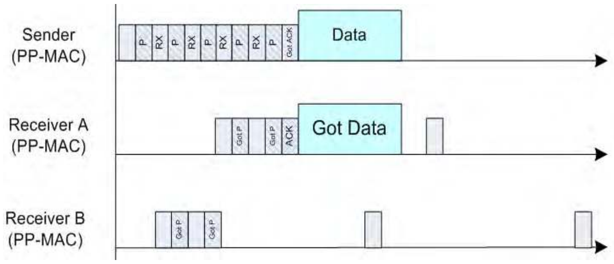


FIGURE 22. **Patterned Preamble in PP-MAC.**

DisAdvantages: Switching between the two phases in the preamble period works as an RTS_CTS and causes unnecessary control packet overhead. The synchronization process after getting the ACK in the ACK preamble phase can cause extra overhead and delay. Scenarios chosen for protocol performance measurement are not justified in certain situations. For example, the protocols will give inaccurate results for the case of dense networks or mobile nodes.

G. RECEIVER-INITIATED MAC (RI-MAC)

The main goal of Receiver-Initiated MAC [84] or RI-MAC is to reduce the idle listening time by minimizing the time the sender and its receiver occupy the channel to find a rendezvous time for exchanging data. As its name reflects in Receiver-Initiated MAC (RI-MAC), the receiver periodically wakes up based on its own schedule and broadcast a beacon to check if any DATA packet is intended for it. After listening for a beacon from the receiver, a sender immediately starts sending the DATA packet to the corresponding receiver. The receiver receives the DATA packets and again broadcasts a beacon which serves as the acknowledgement for the previously received packet as well as the invitation for other DATA packets which are intended for it. Collision can occur if two sender nodes at the same time wish to send DATA packets to the same receiver. This situation can be solved by broadcasting a beacon with a large back-off window. Figure 23 shows the collision handling mechanism used in RI-MAC.

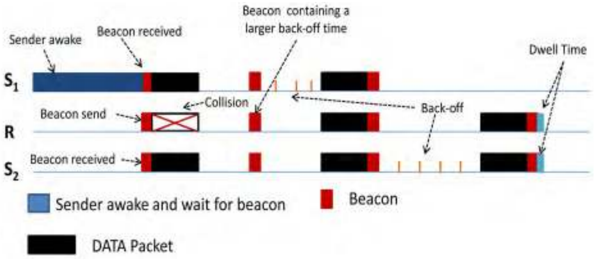


FIGURE 23. **DATA transmission from contending senders in RI-MAC. Receiver R send a beacon to request sender S1 and S2 to start sending DATA. In the case of collision, R sends another beacon with increased BW value to request that sender does a back-off before their next transmission attempt.**

A node will stay awake for a time period called *Dwell time* to receive the queued packets. This time period is adjusted according to the number of contending senders. A beacon can also be initiated by the sender when it has pending DATA frames to transmit and is known as a beacon on request.

Advantages: RI-MAC performs more efficiently than X-MAC in light traffic loads and can handle a wide range of traffic loads. It also performs better in terms of throughput, packet delivery ratio, and power efficiency when compared to X-MAC under the same circumstances. Due to its receiver-initiated property, it can easily handle collision and DATA recovery problems.

H. BEAM

A Burst-aware Energy-efficient Adaptive MAC (BEAM) protocol [85] is proposed to achieve low latency, scalable, and reliability data delivery with less energy consumption. Specifically, BEAM makes an extension of the adaptation algorithm of duty cycle so as to support diverse transmission patterns. Furthermore, the receiver sleep time is calculated based on the size of the payload. There are two operational modes defined in BEAM, i.e., preambles can be sent with or without payload.

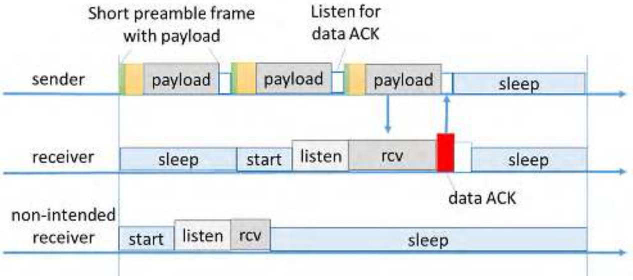


FIGURE 24. **BEAM using Short Preambles with Payload.**

The basic operation mode is that the sender periodically sends short preambles with payload, shown in Figure 24. When a receiver wakes up, it can determine whether or not it is the intended receiver by checking the destination address from the frame header of the preamble. Once the sender receives the ACK for the data, it stops the transmission of the preamble with payload and enters into sleep mode.

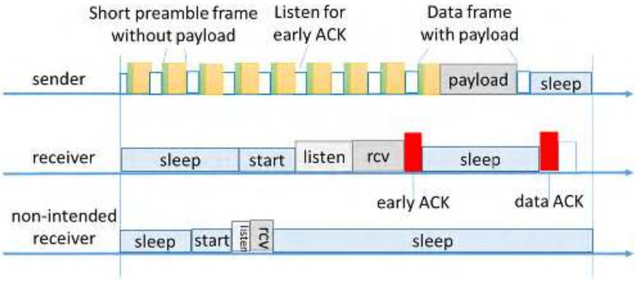


FIGURE 25. **BEAM using Short Preambles without Payload.**

Another operating mode is to send the short preamble frame without any payload, shown in Figure 25. The sender periodically sends the preamble frames until it receives ACK from the intended receiver. Then the sender transmits the data frame with payload, which is acknowledged.

Advantages: The design of short preambles without payload reduces the overhearing time of non-intended receivers so that those receivers can enter sleep mode timely, resulting in energy conservation. BEAM switches between the two modes according to the size of the payload, so as to conserve energy. In addition, BEAM can support hop-to-hop reliable data delivery by incorporating the acknowledgement upon successful data reception.

DisAdvantages: The operation mode of transmitting preamble frame without payload requires at least four message transmissions. Therefore, it is more complex and less robust compared to the basic operational modes.

I. PW-MAC

Predictive-Wakeup MAC (PW-MAC) [86] allows senders to predict the wake-up time of receivers, so as to mitigate idle listening and minimize the energy consumption. The wake-up schedule is determined using a pseudo-random generator. Each node wakes up periodically and sends a beacon to announce that, it is ready for packet reception. After decoding the receiver's pseudorandom parameters, the sender wakes up just before the receivers and starts to transmit data.

PW-MAC introduces the prediction-based retransmission scheme to provide reliable data delivery and low latency. After detecting the collisions, a node enters the sleep mode and wake up at the time based on the prediction. The sender recognizes the collision by receiving a wake-up beacon from the receiver instead of an ACK for the previously transmitted data packet. Then, the sender enters to sleep mode and wakes up at the next predicted wake-up time of the receiver for the data retransmission.

Advantages: PW-MAC enables the prediction of receiver wake-up times at senders. With PW-MAC, packet collision can be reduced.

DisAdvantages: In PW-MAC, every time a node wakes up, it sends a beacon to its potential senders regardless of whether or not that sender has data to send, resulting in an increase of communication packet overhead. Furthermore, the pseudorandom generator parameters are broadcast periodically, which worsens in high network density.

J. EM-MAC

An Efficient Multichannel MAC (EM-MAC) protocol [87] is proposed to enhance the utilization of wireless channels and to improve the efficiency of transmission. This is achieved by allowing the nodes to select the optimal wireless channel dynamically as per the actual channel conditions. EM-MAC can predict receivers' wake-up time and channel condition. It uses multiple orthogonal radio channels, which allows EM-MAC to avoid selecting busy channels and mitigate interference. In addition, EM-MAC avoids using the control channel for data transmission.

Each node selects its wake-up time and channel independently, based on a pseudorandom function. In particular, a node generates two pseudorandom numbers to determine its wake-up time and channel. EM-MAC is a receiver-initiated protocol. A node transmits a wake-up beacon to its potential sender. The sender can predict the wake-up time and channel based on the information in the wake-up beacon. Then, the sender wakes up at just before the wake-up of that receiver and sends data on the predicted channel of the receiver. The receiver sends an ACK to the sender upon successful packet reception. An example of a sender S sends data to sender R is shown in Figure 26.

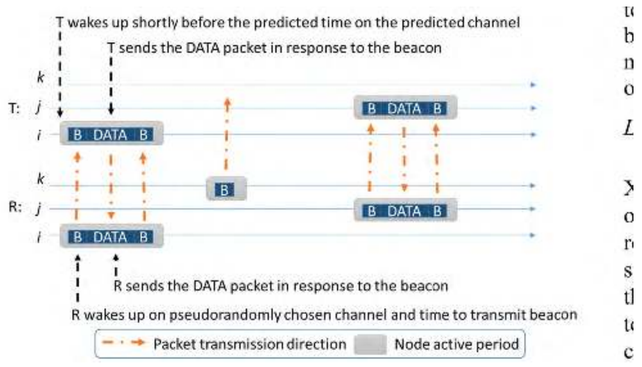


FIGURE 26. **Node S sends data messages to Node R with EM-MAC. Here shows three channels, which are labelled as i, j, and k, respectively. At the time of R's second beacon, none of these nodes has any packets to send to Node R.**

Advantages: Compared to the protocols designed for a single channel, EM-MAC is more robust against wireless interference and jamming. In addition, EM-MAC can handle a large amount and dynamic traffic loads with efficient utilization of multiple wireless channels. EM-MAC can achieve short latency with low duty cycle with reliable data delivery. Compared with other protocols, such as Y-MAC [88] and PW-MAC [86], EM-MAC can achieve significant performance improvement, especially under the dynamic channel conditions.

DisAdvantages: In EW-MAC, every node needs to send the beacon each time it wakes up, increasing the protocol overhead. The pseudorandom generator is invoked twice to generate the value for wake-up channel and time calculation, which in future may increase the overhead.

K. AS-MAC∗

An Asynchronous Scheduled WSN MAC protocol (AS-MAC∗) [89] allows nodes to store the schedules of their neighbor nodes. Neighbor nodes wake up in an asynchronous manner to avoid interference. During the network initialization phase, each node maintains a neighbor table that contains the scheduling information of neighbors. Then, a node enters the period sleep and listening phase. A sender wakes up at the same wake-up time of its neighbor when it has a packet to send.

AS-MAC∗ can provide reliable data transmission supported by ACK upon successful data reception. After the sender transmits a data packet, it stays awake for another short period and waits for the ACK to confirm the successful delivery of that data packet. If the sender does not receive the ACK when the waiting period times out, it enters a sleep state and retransmits the data in the next wake-up time. The retransmission follows exponential back-off time with a number of limits.

Advantages: AS-MAC∗ builds on the existing structure of MAC protocol by inheriting the advantages of existing property. In addition, it adds the features of energy saving. Furthermore, AS-MAC∗ can successfully mitigate overhearing and reduce channel contention and latency for data delivery with an asynchronous wake-up schedule of neighbor's nodes.

DisAdvantages: The asynchronous wake-up interval in AS-MAC∗ results in broadcast inefficiency. It happens as neighbors of a sender wake up at different time slots. So it needs to send data individually to each of its neighbor which would have been achieved by a simple broadcast. In addition, each node needs to maintain a one-hop neighbor table, which results in overhead and additional memory usage.

L. RIX-MAC

A receiver-initiated MAC protocol is proposed based on X-MAC [90], called RIX-MAC [91]. In RIX-MAC, the number of control frame sent by senders is reduced through the receiver-initiated wake-up scheduling scheme, which utilizes a similar approach as of RI-MAC [92]. RIX-MAC further reduces the overall number of control packets and incorporates the scheme to prevent a collision, when there are multiple senders and a common receiver.

In RI-MAC, a sender sends a short preamble to its neighbors during the wake-up period. To avoid a collision, a sender keeps listening to the channel for any preamble or ACK from a receiver. RIX-MAC includes two additional fields in the control packets, i.e., duration and wake-up time. With the help of wake-up time, senders are able to predict the wake-up time of a receiver so as to wake up just before the receiver. The duration field contains information about transmission duration of a data packet. A receiver node inserts its wakeup time information into the corresponding early ACK and gets the information of sender's transmission duration. It also inserts this information into the early ACK. When a sender receives the early ACK, it understands the wakeup schedule of the receiver. In RIX-MAC, with the information of receiver's wake-up schedule, a sender wakes up twice in one cycle. A sender first wakes up at the scheduled time for data reception, and then, it wakes up for data transmission at the wake-up time of the receiver.

In RIX-MAC, the collision takes place when multiple senders transmit packets to one receiver. In order to solve this issue, RIX-MAC introduces a random back-off time for the sender, when the senders wake up at the receivers' wake-up time.

Advantages: RIX-MAC can efficiently reduce energy consumption by utilizing the short preambles and allow senders to predict the wake-up time of receivers. With the utilization of back-off time, RIX-MAC can reduce the packet collision.

DisAdvantages: The wake-up scheduling of RIX-MAC requires the nodes to synchronize periodically to adjust the local clock. Therefore, the sender can wake up at the same time of the receiver. However, it incurs overhead and energy consumption.

M. FTA-MAC

A Fast Traffic Adaptive Energy-efficient MAC (FTA-MAC) is a receiver-initiated protocol [93]. The receiver sends a wake-up beacon to initiate the communication. The wake-up interval of the receiver is adapted based on its traffic rate, so as to minimize the idle listing of the sender and reduce the energy consumption of the network.

FTA-MAC employs the Traffic Status Register (TSR) technology [94] to estimate traffic. When a node receives one packet from the sender, it uses bit 1 to mark the TSR corresponding to that node. Otherwise, bit 0 is used to mark the TSR when the node does not receive any data from that sender during its wakeup time. In this way, a receiver maintains a list of TSR of its neighbors, which records the status of neighboring traffic. Specifically, the TSR is not a quantitative estimation of the data rate. Instead, it is an estimation of whether the traffic is increasing or decreasing. Based on the estimated traffic, the receiver adjusts its wake-up interval so as to minimize idle listening time.

In FTA-MAC, there are two phases in communication, i.e., during the network convergence and after the network convergence. During the network convergence time, a wake-up beacon is periodically sent to a receiver to inform its neighbor nodes about its wake-up time. A sender wakes up periodically with an interval according to its data rate. A sender waits for the wake-up beacon from the receiver, before it sends the data. Upon successfully receiving a data packet, the receiver replies an ACK to the sender. To reduce the idle listening of the sender, a receiver tries to wake-up according to the wake-up interval of each sender. After the network convergence time, the receiver schedules its wake-up interval based on the estimated traffic information collected with TSR, so that the idle listening is efficiently minimized.

Advantages: By efficiently utilizing TSR technique, the receiver can adapt its wake-up time based on the estimated traffic from potential senders, so as to reduce the idle listening time. FTA-MAC can significantly reduce the energy consumption.

DisAdvantages: With the blind estimation, TSR technique may converge to a wrong value, resulting in the different value of duty cycle. FTA-MAC cannot respond quickly to dynamic traffic conditions. FTA-MAC is proposed for a network with a star topology, thus, it faces difficulty in utilizing multi-hop scenarios.

N. CR-WSN MAC

A spectrum-aware multichannel asynchronous MAC protocol, called CR-WSN MAC, is proposed [95]. CR-WSN is designed for WSNs with cognitive radio technology. With the cognitive technologies, sensor nodes can opportunistically access to different channels. By leveraging the benefit of cognitive radio in WSNs, congestion and packet loss can be reduced, resulting in reliable data delivery. For the channel acquisition and the data transmission, CR-WSN utilizes an asynchronous duty cycle scheme.

In CR-WSN MAC, the network is composed of Primary Users (PU), Secondary Users (SU), data channels and a control channel. Each PU is assigned with a licensed channel. Assuming SUs are equipped with half-duplex transceivers, one SU cannot transmit or receive a packet through another channel as long as it is currently working on a different channel. When a data channel is not occupied by a PU, it can be used by a SU. A SU follows asynchronous duty cycle. Once it wakes up, a SU senses the data channel and listens to the control channel for requests. The data is transmitted using the common channel of both the sender and receiver. The SU can make a reservation of data channel by exchanging control messages.

There are three phases in CR-WSN MAC, i.e., spectrum sensing process, channel negotiation process and data transmission process. CR-WSN MAC sends several packets with short preambles, which contains the destination node's address. Therefore, besides the destination node, other nodes can switch to sleep mode once they receive the first preambles, so as to conserve energy. Upon receiving the short preambles, the destination node replies ACK with the channel ID to start the data transmission process using the indicated channel.

Advantages: CR-WSN MAC makes use of the benefit of cognitive technology. By opportunistically using data channel, CR-WSN can reduce idle listing, and it does not require network-wide synchronization.

DisAdvantages: With CR-WSN, when the size of data packets increases, there is a higher probability that the PU interrupts the transmission of SUs, resulting in decreased throughput.

VI. TDMA-BASED PROTOCOL

A. ER-MAC

Energy-and-Rate based MAC or ER-MAC [96] is a TDMA-based MAC protocol employing the periodic listen and sleep mechanism introduced in S-MAC. It introduced the term *energy-critically* of a node, which is a measure of the lifetime of the node. Energy criticality of a node is determined by the remaining energy level of the node and the packet flow rate through the node. If E_i is the residual energy level of a sensor node and F_i is the flow rate of the packet from the node then Energy criticality (C_i) of the node for all nodes j in the TDMA-group containing i, can be calculated as:

$$C_i = \frac{E_i}{\max\{E_j\}} + \frac{F_i}{\max\{F_j\}}$$

A node that is more active transmitting is allocated number of slots, and nodes with lower energy level are also critical and are allocated with more transmission slots than its neighbors. The goal of this protocol is to balance energy consumption among nodes to extend the network lifetime.

Two phases are defined in the protocol: *Normal phase* and *voting phase*. Voting phase is triggered locally by a node when its energy criticality falls below a certain threshold (of the previous winner). This node becomes the new leader if its criticality is below the criticality of its neighbor. The leader will have more transmission slots allocated to it, while the rest of the nodes in the group only have one slot.

In the normal phase, if a node owns the current slot, then it sends any available data or sleeps when there is no data available to transmit. If this node does not own the slot, it needs to be awake in order to receive data from its neighbors. If this slot is the second slot of the current leader, the slot is idle and this node goes to sleep.

Advantages: ER-MAC has no packet loss due to the TDMA nature of the protocol, i.e. No two nodes transmit at the same time slot. No contention and control overhead. The voting phase is also integrated into the normal TDMA phase to save bandwidth/overhead. This protocol shows that it is more effective in higher load traffic in terms of the achieved energy savings.

DisAdvantages: ER-MAC does not address the problem in scalability as the slot assignment algorithm are not part of the scope of the paper presented. A node can communicate to other nodes only if its own assigned slot can cause low bandwidth utilization during data transmission.

B. H-MAC

H-MAC [97] is a TDMA-based MAC protocol designed for a star-topology body sensor network that makes use of biorhythms for time synchronization.

Biorhythms are represented by waveform peaks of bio-signals captured by biosensors. Examples of bio-signals are electrocardiogram (ECG) [98], [99], phonocardiography (PCG) [100], and ambulatory blood pressure (ABP) [101], [102]. Waveform peaks are selected because they are the most significant characteristics of bio-signals. They are easy to identify, easily available, and more immune to noise interference.

H-MAC is designed for one-hop star topology BSN. Each sensor node is allocated a time slot during which only that sensor node is allowed to transmit to a common receiver or the network coordinator. The coordinator could be a PDA, a cell phone or a wrist-worn pulse monitoring watch. A network coordinator is responsible for transmitting the network control packets such as time slot scheduling messages and synchronization recovery beacons.

A biosensor [103] may lose its synchronization when the peak detection algorithm fails and the heart rhythm information is lost due to an abrupt change in the heartbeat. To recover this, a resynchronization recovery scheme is activated.

Advantages: In H-MAC, sensor nodes do not need to turn on their radio to receive periodic timing information from a centralized controller, since the synchronization is provided by following the heartbeat (biorhythm).

DisAdvantages: A network coordinator is still required to maintain the network. It is only suitable for infrastructure Body Sensor Networks. Resynchronization control packets still add to energy waste. This also introduces idle listening, since all nodes need to be awake to resynchronize. Single point failure is possible because of the central coordinator failure. The long buffer is needed to store the sensory DATA.

C. ZEBRA-MAC

Zebra-MAC [104] or Z-MAC is a hybrid protocol containing the strength of TDMA in high contention and adaptability and strength of CSMA-based protocol in low contention level.

Z-MAC starts with a network setup phase that is normally run only once at startup and does not run again until some significant change in network topology occurs. In the network setup phase, the following activities are done in sequence: *neighbour discovery*, *slot assignment, local frame exchange*, and *global time synchronization*.

In *neighbour discovery*, each node gathers its one-hop neighbours' lists that contain the neighbour's one-hop neighbours. At the end of neighbour discovery, each node will have a two-hop neighbours list. This list is used as an input to the distributed *time-slot assignment* algorithm to assign time slots to every node in the networks. The time-slot assignment algorithm is scalable and flexible to include a small number of new nodes that join the network at a later time. Based on the list of two-hop neighbours, a node can determine the *local time frame size* or the number of time slots in a frame of a two-hop neighbourhood. As long as there is only one node in its two-hop neighbour, transmitting in the different time slot, the collision will not occur. After this, every node exchanges its frame size and slot number by forwarding them to its two-hop neighbourhood. Finally, all nodes synchronize to the first slot to run the transmission control of Z-MAC.

There are two node modes in Z-MAC: low contention level (LCL) and high contention level (HCL). A node that has a data will transmit (when channel is clear), if the following is true: the node is the owner of the time slot or the node is in LCL mode and wins the channel by contention, or the node is in HCL mode but the current slot is not owned by any of its two-hop neighbours. A node may be in HCL mode when it receives Explicit Contention Notification (ECN) from a node in its two-hop neighbours that experience a high level of contention based on the noise level.

Advantages: As Z-MAC is implemented on top of B-MAC, each node uses LPL where it wakes up periodically to check for a preamble from the transmitter. This makes the energy consumption for idle listening comparable to B-MAC. Throughput is better as compared to B-MAC because of its capability to run TDMA in high contention and CSMA in low contention.

Disadvantages: Though Z-MAC utilizes the property of CSMA and TDMA, it is still not good for event-driven applications. Overhead during network setup phase is very high because of four activities: *neighbour discovery*, *slot assignment, local frame exchange*, and *global time synchronization*.

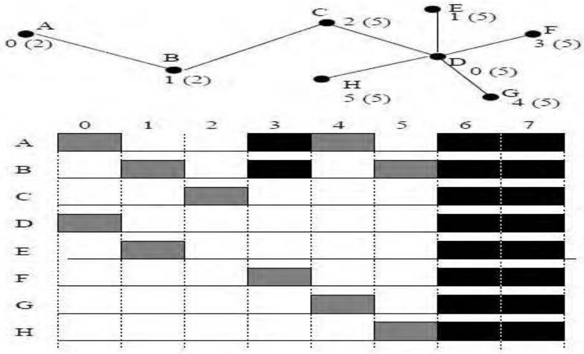
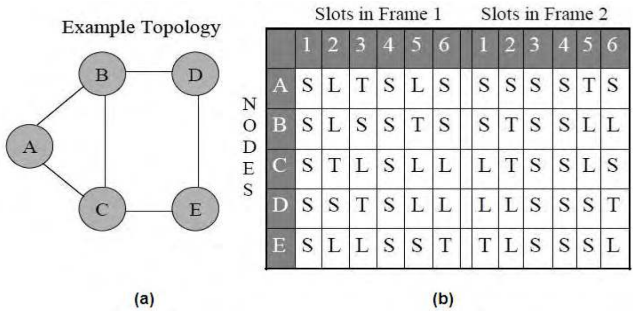


FIGURE 27. Example of network topology and time slot schedule in Z-MAC.



	Slots in Frame 1						Slots in Frame 2					
NODES	1	2	3	4	5	6	1	2	3	4	5	6
A	S	L	T	S	L	S	S	S	S	S	T	S
B	S	L	S	S	T	S	S	T	S	S	L	L
C	S	T	L	S	L	L	L	T	S	S	L	S
D	S	S	T	S	L	L	L	L	S	S	S	T
E	S	L	L	S	S	T	T	L	S	S	S	L

FIGURE 28. Example topology and possible transmission schedule.

D. RANDOM INTERFERENCE MAC

Random Interference MAC or RI-MAC [105] is not a general-purpose protocol but intended for multi-hop broadcast which has some specific applications in wireless sensor networks such as query or code distribution from the base station to the entire network. In this protocol, energy conservation, fairness, and adaptability have more importance over channel utilization.

To set the transmission schedule, firstly each node chooses a random slot in a frame as its Transmission (T) slot. After that, each node broadcasts its transmission schedule to other nodes, which is done in unscheduled listening during the setup phase. Each node then has the information of other nodes transmission schedule and completes its remaining slots in the frame as either Listening (L) or Sleeping (S). The rule is if there is only one neighbor transmitting, then listen. If there are two or more neighbors transmitting, then sleep.

Advantages: RI-MAC does not require synchronized clocks but a node synchronizes with other nodes based on the timing information in the receive packets. RI-MAC's adaptability to network changes only requires its one-hop neighbors' information for its scheduling algorithm.

DisAdvantages: Energy is wasted during neighbors schedule discovery during setup phase and when there are two nodes transmitting in the same timeslot. Each node has to keep the location information of his one-hop neighbor node which has to be updated every time a node joins or leave the network. Unfortunately, RI-MAC does not support the case when nodes are mobile and they can leave and join the network.

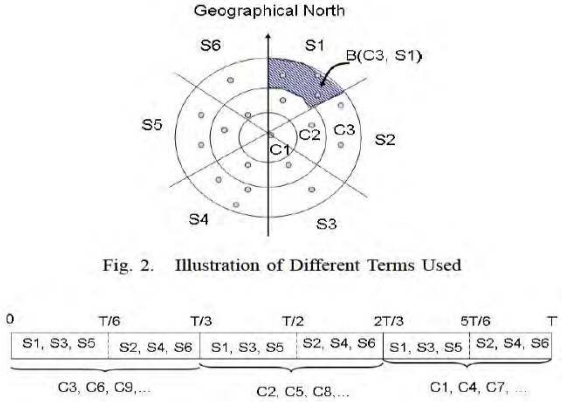


FIGURE 29. Allocation slots from superframe in RT-MAC.

E. REALTIME MAC

Realtime MAC [106] or RT-MAC is TDMA-based MAC protocol that guaranteed the transmission delay from nodes in the cluster to the cluster head is upper-bounded. RT-MAC introduced a new technique to assign timeslots for node transmission to achieve channel re-utilization. Sensing area is divided into grids or clusters, and each cluster has a cluster head. It is desirable that the cluster head position is in the center of the cluster, and it is stationary. It is assumed that the angle of each node with respect to the north of the cluster head is known.

The self-configuration process of sensor nodes starts with each node finding its hop distance to the cluster head. Each node broadcast a message with an ID and a counter that is incremented whenever it reaches a node. A node that receives a new broadcast message simply re-transmits again. The ID parameter is used to prevent incrementing counter and re-transmitting twice if the same broadcast message has been received previously. When the cluster head has received this message, it will transmit/broadcast an ACK message that eventually is going to reach the source node. As the source node is going to receive multiple ACKs from different paths, it needs to find the minimum hop distance based on the counter value in the ACK packet. RT-MAC uses CSMA/CA protocol during this stage.

Time slots are assigned to the sensor nodes such that they can be reused by sensors which do not interfere with each other. Slots allocation is based on the number of hop-distance from node to cluster head.

If a node has a packet to send, it waits for its time slot to transmit the packet. While it is waiting, the node is allowed to sleep when they are not receiving or transmitting any packet.

In RT-MAC delay analysis, it is shown that the maximum delay from any node to the cluster head is bounded determined by the node position in the ring, the number of nodes in internal rings, the number of slots in the ring, timeslot duration, and per-hop transmission time.

Because of the slot assignment, it is possible that a node is neither transmitting nor receiving at a particular time slot. This allows a node to sleep to conserve energy.

RT-MAC suffers higher latency and energy consumption as compared to the S-MAC. However, it reaches to near S-MAC in term of energy consumption when the event generation rate is high.

Advantages: RT-MAC provides delay-guarantee packet transmission and suitable for real-time applications.

DisAdvantages: However RT-MAC provides delay-guarantee it suffers higher latency and energy consumption. In the case of heterogeneous node transmission range, it will suffer from high collision because of its channel re-utilization property.

F. Y-MAC

Y-MAC [107] is a TDMA-based MAC protocol with a frequency channel hopping mechanism to reduce latency, especially in high traffic loads. In a typical TDMA protocol, all nodes need to wake up to receive packets from a node which is in its transmission slot. This results in idle listening and overhearing. However, in Y-MAC each node is assigned its receive slot with the tradeoff of non-collision free transmission between senders intending to transmit to the same receiver node.

A Superframe is divided into the broadcast period and unicast period. The broadcast period consists of three contention slots. The unicast period consists of a number of time slots. The number of time slots is carefully selected as there is a trade-off between a number of time slots and delivery latency. Higher numbers of time slots cause higher latency as nodes have to wait longer until their time slot has arrived. Figure 30 shows the lightweight channel hopping mechanism in Y-MAC.

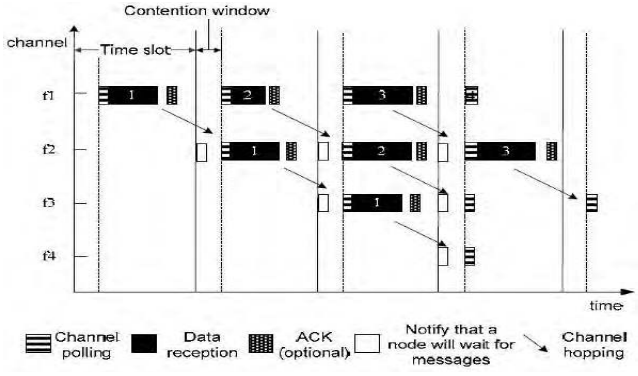


FIGURE 30. Lightweight channel hopping mechanism in Y-MAC.

At the beginning of the broadcast period, each node wake-ups and switches to the base channel. A node that has data to transmit needs to contend for the channel and transmit. If there is no data to transmit, or node does not receive any data, it goes to sleep mode, and wait until its reception time slot. At the beginning of its time slot, sender and receiver nodes set their frequency to the base channel. Upon successful reception, the receiver sends an acknowledgement to the transmitter, if requested. Nodes need to sample the medium only during the broadcast and its own unicast reception slot.

To reduce latency and message buffer overrun during heavy traffic, the channel-hopping mechanism is employed. If a node receives a message on the base channel, it hops to the next channel to receive the next message. Any nodes with a pending message destined to the same receiver also hop to the same channel and compete again. To guarantee per node fairness, contention winner's back-off timer range is limited for the next transmission.

Y-MAC uses distributed time slot assignment to control overhead evenly. Each node maintains a *slot allocation vector* that contains the node and its one-hop neighbourhood's occupied time slots. This slot allocation vector is broadcasted with the control message. Each node collects the occupied time slots information from the control messages. When a network partition occurs, the time slot of the node that is no longer part of the network needs to be released.

In performance evaluation, Y-MAC is compared with LPL and Crankshaft [108] in single-hop and multi-hop environments. Y-MAC and Crankshaft [109] are more energy efficient than LPL because the low overhearing problem is reduced by allocating receive time slots to the nodes. Y-MAC's latency is lower than that of Crankshaft and LPL. Y-MAC's reception rate is also better compared to LPL and Crankshaft due to its multi-channel nature.

Advantages: Y-MAC can handle the busty messages effectively under high traffic conditions while maintaining low energy consumption because it exploits multiple channels for message reception and transmission. Y-MAC achieves higher throughput and reduces messages delivery latency by hopping the next radio channel if a node has pending messages for the receiver.

DisAdvantages: Control packet overhead is high because of the frequent periodic exchange of these packets.

G. GlacsWeb MAC

GlacsWeb MAC or GW-MAC [110] is a TDMA-based MAC protocol specially developed for networks deployed in glacial environments which are very harsh and may cause very unreliable radio communication between sensor nodes. In such cases, it is necessary to design custom-made hardware and a suitable MAC protocol: GW-MAC. It is not required for the sensors to monitor the glacier very often. This allows nodes to sleep for very long durations, wake up for communication to transmit, listen or relay data packets, and then go to sleep again. Nodes may occasionally wake up for sensing activity and sleep again. Like other TDMA protocols, in GW-MAC, time is divided into frames and frames into slots. The number of slots per frame is determined by the number of nodes in the network. The number of slots may be adjusted in the network discovery phase. Nodes can be reassigned to different time slots depending on the topology of the network to efficiently and fully utilize every communication frame.

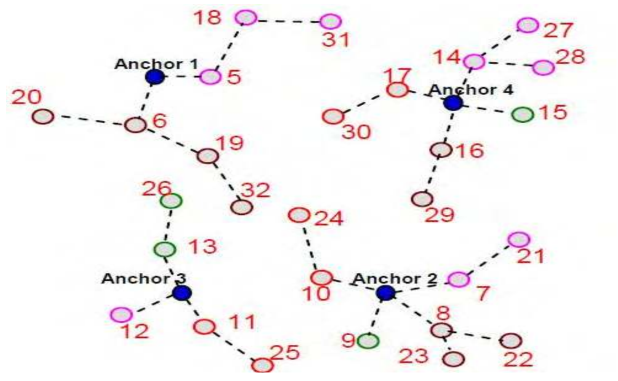


FIGURE 31. Network after configuration.

Time slot assignment is done on the base station. Figure 31 shows a network after configuration.

The base station is located at the glacier surface and is connected using wired-serial communication to a few anchor nodes inside the glacier. The anchor nodes communicate with sensor nodes wirelessly.

GW-MAC initiates network discovery phase and network configuration phase every 1 to 7 days depending on the system behaviour and other factors such as weather. The purpose of network discovery phase is to find the nodes within range of anchor nodes and the nodes outside of the range of anchor nodes. In the network configuration phase, the base station assigns an optimized time slot for each node and node gateways.

A node that has not been communicating for a period of time, which could be a missing node, is programmed to only listen until the next network discovery. This is to prevent a collision if this node wants to transmit in its assigned timeslot. To minimize overhearing, nodes are active only during their parents' and children's time slot.

Advantages: GW-MAC is suitable for remote area monitoring where DATA collection is the main concern rather than delay or latency. It prolongs the network lifetime significantly because of nodes only wake-up for few minutes in a day rather than waking up every few seconds.

DisAdvantages: GW-MAC cannot be used as a general purpose MAC protocol. Deployment cost of the network in GW-MAC will be very high because it needs wired anchors as well as wireless sensor nodes.

H. CBTW

CBTW [111] is a distributed, clustering-based protocol with intra-cluster coverage. It is based on the existing Time Division Multiple Access Wake Up (TDMA-W) protocol. The idea is to utilize assigned slots in the nodes only for receiving and transmitting the DATA; otherwise, keep the radio off to avoid idle listening. Wakeup packets are used to activate the sleeping nodes, accelerating the receive response.

CBTW operations are divided into rounds. Each round in the protocol includes:

1) Set-up phase, clusters are organized with the selection of cluster head nodes (intra-cluster coverage) and routing trees are constructed.
2) Working phase: data gathering from the nodes to base stations takes place.

CBTW uses TDMA-W for intra-cluster communication and TDMA schedule for inter-cluster communication. Each node in the cluster send its corresponding DATA to the cluster head in its assigned slot, then cluster head sends this DATA to the sink by the TDMA-W method.

Advantages: Data aggregation in the cluster head and packet passing from cluster to cluster head can reduce the duplicate packet overhead and data traffic.

DisAdvantages: Cluster formation is an overhead and even one cluster failure during data transmission can cause severe packet loss and overhead. Latency is high and hence not suitable for event-driven applications. Tree formation is difficult in frequently changing network scenarios.

I. SEHM

SEHM [112] is a clustering based and hybrid medium access protocol for large-scale wireless sensor networks. It utilizes the best features of both contention-based and scheduling-based protocols to achieve the significant amount of energy efficiency and provide better data packet delivery.

SEHM can be divided into two phases, First, cluster formation phase and second, data transfer phase. Clustering of the sensor network is done by using the Ext-HEED [113] algorithm. Each cluster is controlled by a Cluster head (CH). While choosing the cluster head both residual energy and communication cost is considered. Clustering algorithm execution follows four phases: *initialization phase*,*repetition phase*,*optimization phase*and *finalization phase*. During the data transmission phase cluster head (CH) is responsible for controlling and distributing the channel access between the sensor nodes within the cluster and then sending this data to the base station (BS). *Intra-cluster communication* (communication inside a cluster) consists of four phases: *Synchronized phase*, *request phase*, *receive scheduling phase* and *data transfer phase*, while *inter-cluster communication* (communication from Cluster head (CH) to Base station (BS)) consist three phases: *synchronized phase*, *receive scheduling phase* and *data transfer phase*.

OMNeT++ [114] is used for simulation, while EYES wireless sensor nodes are used as a model. The comparison is done with the S-MAC protocol while using the matrix energy consumption, average packet delay, and packet delivery.

Advantages: SEHM is more energy efficient in high traffic because of no collision during data transmission (TDMA approach benefit). Its data delivery ratio is high because of collision-free packet transmission.

DisAdvantages: Though it is energy efficient it still suffers from high average delay because of its TDMA approach during data transmission. Running clustering algorithms and

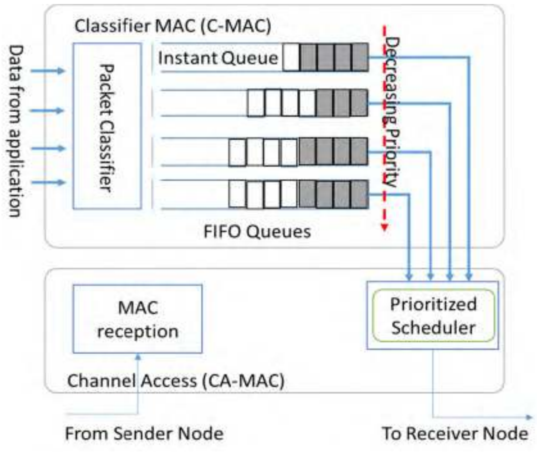


FIGURE 32. **PRIMA Functional Diagram.**

synchronization is an extra overhead for the SEHM MAC protocol.

J. PRIMA

An energy efficient priority based MAC (PRIMA) protocol [115] is proposed for WSNs based on Q-MAC [116]. PRIMA has two main phases, i.e., a clustering stage and a channel access stage. The design of the clustering algorithm is to provide network scalability. PRIMA makes use of a variant of LEACH [117]. The decision for a node to be a Cluster Header (CH) is with a probability p. After a node is set as the CH, it broadcasts the result. Non-CH nodes choose the CH that is reachable with the least communication energy. The role of the CH is rotated for the purpose of workload balancing and energy conservation.

In PRIMA, a hybrid channel access is proposed based on TDMA and CSMA. PRIMA utilizes both Classifier MAC and Channel Access MAC as its channel access mechanism. The packets are classified and inserted into different priority queues based on their importance.

For intra-cluster communication, CHs broadcast the scheduling messages to all nodes within the cluster. For communication between CHs to the base station (BS), the BS distributes the schedule between CHs, with the assumptions that all CHs have content to submit to the BS.

Advantages: PRIMA can achieve significant energy conservation by combining the benefits of both contention and scheduled based protocols. In addition, PRIMA can guarantee the QoS for diverse traffic types by utilizing priority queues. Therefore, more importance packets have higher priority to access the channel, thus resulting in low latency.

DisAdvantages: In order to schedule the transmission slot for all CHs in the network, BS needs to understand network topology. However, it results in increased overhead and energy consumption. The energy depletion is more significant as the network size increases.

K. RMAC

Receiver-Driven Medium Access Control (RMAC) [118] is a TDMA approach to provide collision-free transmissions. RMAC is composed of three stages, i.e., neighbor discovery, timeslot allocation, and scheduled transmission. During the neighbor discovery stage, each node maintains a two-hop neighbor table. Nodes within two-hop will not be assigned to the same timeslot. During the data transmission phase, receivers only wake up and listen to the channel during the time slots assigned to them. For the rest of timeslots, receivers remain asleep. The assignment of time slots is based on the distributed scheduling solution (DRAND) [119].

RMAC introduces timeslot stealing mechanism to enable other senders to use the unused timeslots. For each timeslot, there is a primary sender node and secondary sender node assigned. The secondary sender node listens to the channel to determine whether the primary sender node is occupying the channel or not.

Advantages: In RMAC, receiver nodes assign the timeslots to their sender nodes, thus eliminating possible channel contention and packet collision. With the timeslot stealing mechanism, the channel utilization is increased and latency for packet delivery is reduced.

Disadvantages: In RMAC, whenever the topology of the network changes, neighbour discovery and timeslot allocation need to be performed. This requires the exchange of HELLO messages resulting in considerable overhead and energy consumption. In addition, the timeslot stealing increases energy consumption as a secondary sender needs to listen to the channel.

L. QUEEN-MAC

An adaptive energy-efficient MAC protocol (Queen-MAC) [120] is proposed for Dyadic grid quorum system, in which sensors are assumed to be uniformly distributed and the sink node is located at the corner. Specifically, sensors are grouped according to their hop distance from the sink node. Another assumption is that all sensors are time synchronized, which is under the same assumption as [121], [122].

Queen-MAC defines two types of time slots, i.e., quorum timeslots and non-quorum timeslots. Specifically, during quorum timeslots, nodes wake up for message exchange, while during non-quorum timeslots, nodes switch to sleep mode for energy saving. Queen-MAC introduces the algorithm to allow nodes that need to exchange data, to be awake at the same time slot. Furthermore, the wakeup frequency of a node is determined by its traffic load. Therefore, energy conservation can be achieved with the reduction of wake-up times. In addition, Queen-MAC makes use of multiple channels to concurrently transmit data. Each group of nodes selects four frequencies as their unicast and broadcast frequencies. Queen-MAC assigns the channel in a way that two-hop groups of nodes do not communicate on the same channel.

Advantages: Queen-MAC supports multi-channel access while it schedules the wake-up and sleep of nodes. Both simulation and theoretical analyses demonstrate that Queen-MAC can prolong network lifetime.

DisAdvantages: Queen-MAC does not provide the solutions for packet collisions. Nodes near the sink nodes have higher traffic load and data rate, resulting in increased latency and decreased packet delivery ratio.

M. BEST-MAC

A bitmap-assisted efficient and scalable TDMA-based MAC (BEST-MAC) is proposed in [123] to support diverse traffic with short latency and significant energy conservation for cluster-based topology in WSNs. In one communication round of BEST-MAC, there are two phases: a Setup Phase (SP) and a Steady State Phase (SSP). SSP is divided into several sessions, each of which consists of one control slot, an announcement periodic Contention Access Period (CAP) and multiple data slots. During the phase of SP, the Cluster Head (CH) allocates the time slot for all member nodes in the cluster with CS_ALLOC message. To adaptively handle traffic load, BEST-MAC uses the time slots with tiny size, such that nodes need to wait for less time for transmission. Therefore, the tiny time slot can enhance throughput and reduce energy consumption.

BEST-MAC employs the knapsack algorithm for allocation of the data slots; with the objective to reduce the time it takes for a node to complete transmission. The knapsack optimization algorithm can utilize wireless channel efficiently and achieve short latency for packet delivery. In addition, BEST-MAC also employs short node address format to reduce energy consumption and control overhead.

Advantages: The design of small time slots in BEST-MAC can adaptively handle a different amount of traffic. In addition, energy consumption is further reduced by incorporating one-byte short address to identify the unique node.

DisAdvantages: The cluster formation and time slots allocation require the exchange of a large number of control messages from time to time. The energy consumption resulting from those control overhead is significant to WSNs. Besides, the time slots allocation of a cluster depends on the cluster head. Once the cluster head fails, the data transmission within that cluster gets affected.

VII. FDMA-BASED PROTOCOL

A. MMSN: MULTI FREQUENCY MAC

Multi-Frequency MAC or MMSN [124] is one of the first multi-frequency MAC protocols for WSNs. MMSN consists of two aspects: *frequency assignment* and *media access*. In frequency assignment, each node is assigned a physical frequency for data reception. The assigned frequency is broadcast to its neighbours to inform other nodes of the frequency used to transmit unicasts packet to each of its neighbours. Frequency assignment is performed at the beginning of deployment and also infrequently at other times for adaption to system ageing.

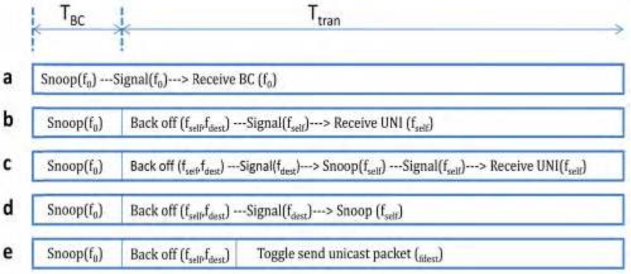


FIGURE 33. Different scenarios of unicast transmission in MMSN.

There are four frequency assignment schemes: *exclusive frequency assignment, even selection, eavesdropping, and implicit consensus.*The outcome of the *exclusive frequency assignment* (EFA) is that different frequencies are assigned to different nodes within any two-hop neighbourhood. EFA requires that the number of frequencies is at least as many as the number of nodes in the two-hop neighbourhood. *Even-selection* is an extended EFA, whereby the number of physical frequencies is not enough for all two-hop neighbours, and therefore the least chosen frequency is randomly chosen. In *Eavesdropping*, each node takes a random back-off before it broadcasts its physical frequency decision. During the back-off period, each node records any physical frequency decision overheard. The *implicit consensus* is similar to EFA, but it makes use of pseudo-random number generators to calculate the frequency number. Zhou *et al.* [124] found that *even-selection* has lesser number of frequency conflicts compared to *eavesdropping*because the selected frequency is the least preferred within two-hop neighbours, whereas in eavesdropping, nodes only overhear frequency decisions of one-hop neighbours. Even-selection also consumes less energy compared to eavesdropping. Even-selection performs better in a static network, and eavesdropping performs better when network topology changes frequently and the network is highly loaded.

The advantage of any multi-frequency protocol is that more than one node can transmit and receive at the same time. Channel is more utilized if there are more simultaneous transmissions.

In MMSN, a superframe is divided into broadcast contention period and transmission period. There is one frequency reserved in the broadcast period and also reused in the transmission period for unicast transmission.

Advantages: Energy efficiency is improved by using multiple physical frequencies. MMSN utilizes multiple frequencies to facilitate a node to transmit/receive at the same time. Exclusive frequency assignment and implicit consensus guarantee that the nodes within two hops are assigned different frequencies.

DisAdvantages: MMSN requires time synchronization during media access in order to provide efficient broadcast support, but it does not take advantage of the synchronization service to resolve conflicts or improve the scheme.

During the broadcast period, a node checks (*snoops*) the broadcast frequency for broadcast transmission from other nodes and transmits broadcast packet to other nodes, if there is data to transmit. During transmission period, a node checks its self-frequency for any unicast transmission to it and switches to the *destination* node's frequency to check if the destination node is busy, and switches back to its self-frequency (*toggle snooping*). In this way, the node will know if there is another node trying to transmit a packet to it and if the destination node is currently receiving packet transmission from another node. If the destination is not busy, this node transmits the unicast packet with a technique called *toggle transmission* to reduce collision.

B. TIME-FREQUENCY MAC

Time-Frequency MAC or TF-MAC [125] is a hybrid of CSMA/TDMA/FDMA protocols. A super-frame is divided into two periods: contention access period and contention-free period. During the contention period, or control slot, all nodes monitor the default frequency for exchanging control messages to maintain the protocol. Contention-free period is divided into N_t time slots which are used to send/receive DATA packets.

If N_f frequencies are available, then each node will be given N_f transmission slots, where each slot is assigned with different frequencies for transmission. For the reception, each node is assigned a single receiving frequency that is used to receive data in its reception slot. Each node has one reception slot from each neighbour. Figure 34 shows an example of TF-MAC time slot schedule with two frequencies available.

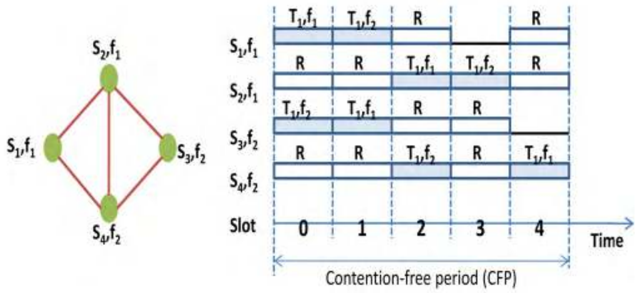


FIGURE 34. Example of TF-MAC time slot schedule with two frequencies available.

TF-MAC consists of frequency assignment and media access. *Frequency assignment* in TF-MAC is that each node randomly chooses one of N_f frequencies as its receiving frequency and broadcast its selected frequency to its neighbours. When nodes are still not part of the network or passive nodes, they would not be assigned a time slot for its transmission. Even so, passive nodes are required to monitor the control slot and transmit during this slot when it wants to join the network by first initiating time-slot assignment process. This process involves passive nodes broadcasting timetable request packet to every neighbour, and every neighbour replying with their timetables. The outcome of the time-slot assignment is collision-free transmission between the nodes (not always the case when two or more passive nodes start activation process simultaneously). Finally, the node broadcast transmission-slot-announcing packet to its neighbours. Since passive nodes are only allowed to access the control slot, collision is bound to occur when two or more passive nodes broadcast timetable request simultaneously.

For data transmission, each node has a timetable used during the contention-free period. Each node timetable contains N_t number of slots, and each slot contains the type of slot and the frequency used for transmission in the slot.

Advantages: Throughput is high because of utilizing many different frequencies for DATA reception and transmission. Average packet delay is low because of the utilization of different frequencies. TF-MAC's performance increases when it has a higher density of nodes in the network.

DisAdvantages: Though TF-MAC performs better in terms of throughput and average packet delay, its energy consumption is high because of its approach of waking-up nodes for listening or transmitting. The average delay for new nodes joining the network is high because it will take several consecutive frames in the timetable gathering process. TF-MAC performance comparison is not provided in the literature.

C. HyMAC HYBRID

HyMAC [126] is a hybrid MAC layer protocol combining the properties of both TDMA and FDMA schemes. In HyMAC, a super-frame is divided into two periods: *scheduled-slots* and *contention-slots*. Slot durations during both periods are determined by the duration to transmit a packet with the maximum size. The base station is responsible for assigining time slot and frequency to each node. HyMAC performance is independent of its underlying synchronization protocols. However, it performs better in a platform which employs out-of-band hardware synchronization such as FireFly. Contention period is used for broadcast purpose where all nodes switch their radio to the same frequency.

Scheduled and *unscheduled* nodes perform LPL and select a slot randomly in the contention period and send HELLO packets to the base station. When a node hears a HELLO packet from a node within its one-hop distance, it updates the neighbor list which is to be in included in the next HELLO packet transmission of that node. The base station collects the HELLO packets from all the nodes, constructs a schedule and then sends it to each node in a SCHEDULE packet. The scheduling algorithm constructs a tree, with the base station as the root. Each node has a parent only to which it can send DATA packets. When there are conflicting neighbors and if the nodes are siblings, then one of the nodes is assigned with a different time slot. Otherwise, one of the nodes is assigned with different frequency.

HyMAC performance evaluation is based on the number of potential conflicts of the scheduling algorithm, compared against the two algorithms proposed in MMSN, namely even-selection and eavesdropping. It is shown that, even with two available frequencies, HyMAC produces zero potential conflict regardless of node density, while potential conflicts in MMSN increase as the node density increase.

Figure 35 shows the operation of HyMAC scheduling algorithm.

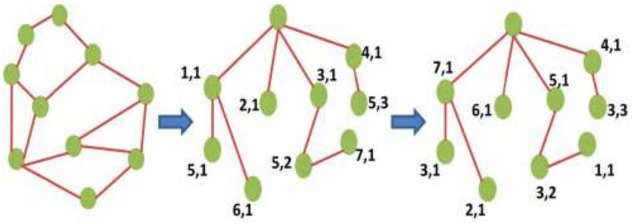


FIGURE 35. The operation of HyMAC scheduling algorithm.

Advantages: HyMAC is best suited for sensor network applications like real-time voice streaming because of its high throughput and low end-to-end delay. HyMAC achieves zero collision while utilizing the multiple frequencies available in MICAZ [127], TELOS [128] and FireFly [129].

DisAdvantages: Control packet overhead is high because of HELLO packet exchange when a new node joins.

D. ECO-MAC

ECO-MAC [130] is a duty cycled and hybrid MAC protocol combining CSMA and FDMA. In ECO-MAC, the sender and receiver nodes need to agree on a random sub-band frequency specified by the sender node before data transmission. Then the node pair keeps the channel for a fixed time slot. This time slot (TS) is fixed as needed by the application. Time slot allocation is done according to CSMA/CA contention techniques and is not cyclic as in TDMA.

The available frequency is divided into several sub-bands. The first sub-band is used for synchronization, the second one is dedicated to exchanging of control packets and the rest are used for data transmission between nodes. Figure 36 shows an example of non-collision transmission in ECO-MAC.

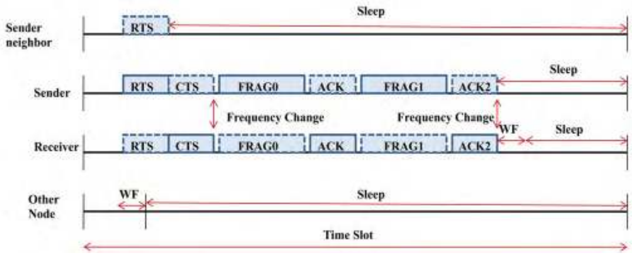


FIGURE 36. Example of non-collision transmission in ECO-MAC.

In this protocol, media access is similar to S-MAC or other duty-cycled protocols but data transmission is done in randomly selected sub-band frequency specified in the RTS packet. Other nodes that are not involved in the incoming communication put themselves to sleep immediately after receiving RTS packet. The pair of nodes involved in DATA transmission/reception keeps the channel for a fixed period of time referred to as Time slot (TS). For the first time, the synchronization process is initiated by the base station (BS) in the initialization phase. After that, it becomes distributed on all the nodes during the lifetime of the network. A new node joining the network needs to know the beginning of the current time slot to synchronize. A node will resynchronize itself again when it does not detect a neighbour for a given period of time.

ECO-MAC shows much less energy consumption during both light and heavy load traffic compared to S-MAC. This is because of the access technique that reduces contention for the first attempt.

In terms of latency, ECO-MAC shows better performance compared to S-MAC. ECO-MAC also shows higher throughput compared to S-MAC.

Advantages: ECO-MAC uses a dedicated channel for synchronization and control packet. Synchronization process in the network is distributed among nodes which help to achieve robustness against the idle listening. Energy consumption is less, especially during low traffic because of not listening to the channel during the time of first packet transmission.

DisAdvantages: "Fixed time slot (TS) can cause a higher degree of delay in the transmission of DATA packets." There are no experiments on a number of frequencies vs throughput.

E. C-MAC

C-MAC [131] is designed to exploit concurrent wireless channel access according to the empirical power control and the physical interference model. It is designed to achieve high-throughput in high traffic scenarios for data-intensive sensing applications.

C-MAC utilizes the transitional relationship between the Signal-to-Interference-plus-Noise-Ratio (SINR) to the Packet Reception Ratio (PRR) and enables concurrent transmission of sensor nodes even though they are within the each other's interference range. It chooses the transmission power such that it will maximize the total throughput of active links. Figure 37 shows a complete process of data block transmission in the transmission engine.

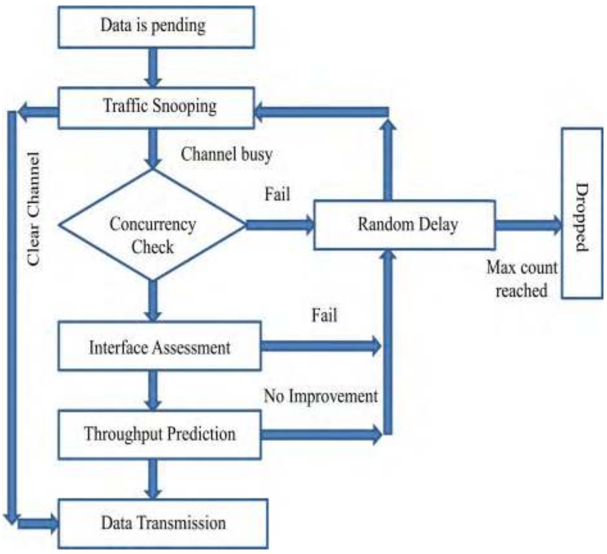


FIGURE 37. A complete procedure of transmitting a data block in the concurrent transmission engine.

TABLE 2. Comparison of surveyed MAC protocols for WSNs.

No	MAC	Year	Contention/ Schedule-based	Basic concept	References	Performance Evaluation	Source of Energy Waste				
							Collisions (Receiver)	Idle listening (Receiver)	Overhearing (Receiver)	Over-emitting (Transmitter)	Control packets overheads
1	S-MAC	2002	Synchronous	Active/sleep duty cycle with fixed period	PAMAS,	802.11	Broadcast of SYNC and control packets packets in virtual cluster	DATA period during low traffic	DATA period	None	SYNC: for synchronisation RTS,CTS, ACK: collision avoidance
2	ERMAC	2003	TDMA	More time slots are assigned to more energy-and-rate-critical node	S-MAC	TDMA,	None	when its not in its time slot	when its not in its time slot	None	Vote packet, radio-mode packet
3	T-MAC	2003	Synchronous	Active/sleep duty cycle with timeout mechanism to end active period	S-MAC	S-MAC, CSMA	Broadcast of SYNC and control packets packets in virtual cluster	minimized using timeout	minimized using timeout	None	SYNC: for synchronisation RTS,CTS, ACK: collision avoidance FRTS. early sleeping problem prevention
4	WiseMAC	2003	Asynchronous	Uses dynamic-length preamble based on traffic load and synchronised with receiver wake-up schedule	802.15.4	802.15.4	for two transmitter wanting to transmit to same receiver node	during wakeup period	Transmission of redundant DATA packet during low traffic	Transmission of redundant DATA packet during low traffic	wakeup preamble, ACK
5	B-MAC	2004	Asynchronous	Uses extended preamble sampling, i.e node keep awake until data is received.	WiseMAC, S-MAC, T-MAC,	S-MAC, S-MAC/AL, T-MAC	When there are two hidden transmitter nodes transmit premable to a receiver node	during wakeup period	when receiving preamble	Long Preamble	Long Preamble
6	D-MAC	2004	Synchronous	Staggered duty-cycled wake up schedule	S-MAC, T-MAC, PAMAS, WiseMAC	T-MAC, S-MAC	Between nodes on the same level	RX period of nodes on lowest level	None	None	MTS (More to send), ACK
7	EEDO-MAC	2005	Synchronous	similar to S-MAC, duty cycle is increased when node hears any communication withint carrier sensing range	S-MAC, DS-MAC, PC-MAC	S-MAC, S-MAC/AL	Broadcast of SYNC and control packets packets	higher due to increase in duty cycle	higher due to increase in duty cycle	None	SYNC, RTS,CTS, ACK. Required for synchronisation and collision avoidance
8	TEEM	2005	Sync	Similar to S-MAC, different control packets to indicate if there is or no data to transmit, allowing neighboring nodes to sleep earlier	S-MAC, T-MAC, DS-MAC	S-MAC	Broadcast of SYNCrts, or SYNC packets	SYNCdata period when no SYNC	None	None	SYNCrts, SYNC. Required for synchronisation and collision avoidance
9	Z-MAC	2005	TDMA/CSMA	TDMA in high contention, CSMA in low contention	CSMA, TDMA, S-MAC, T-MAC, B-MAC, PTDMA,	B-MAC, PTDMA, SIFT,	Minimized during low traffic	during wakeup period checking for preamble	used to detect duplicate ECN	None	ECN to notify neighboring nodes of high-contention level
10	MF MAC	2006	Asynchronous	Uses short preamble containing receiver's ID and sequence number to allow receiver to sleep prior to receiving data	S-MAC, S-MAC/AL T-MAC, WiseMAC, B-MAC	Wise-MAC	Transmission of micro frames	during wakeup period	when receiving preamble	Micro-frames	Micro-frames
11	MMSN	2006	CSMA/FDMA	Toggling frequency sensing and transmission	S-MAC, T-MAC, MMSN WiseMAC, B-MAC CSMA-MAC TRAMA, LMAC	CSMA	reduced by using multiple frequencies and toggle snooping/transmission	during transmission period, snooping on idle channel	snooping on busy channel	preamble during toogle transmission	During frequency assignment
12	RI-MAC	2006	TDMA	distributed scheduling: each node randomly selects transmission slot, and set itself into different state depending of other nodes transmission schedule, intended for broadcast only	TDMA, S-MAC, T-MAC, TRAMA, Z-MAC, TSMA	CSMA	when more than one nodes broadcast in the same time slot	during listen period when nothing broadcasted	None, all are broadcast message	None	Scheduling
13	R-MAC	2006	Synchronous	uses control packet to setup mutli-hop path such that the nodes are awake when its time to communicate, or sleep otherwise	S-MAC	S-MAC	Broadcast of SYNC packets	DATA period during low traffic	DATA period	None	SYNC, PION, ACK. Required for synchronisation and setting up multi-hop path

C-MAC has the following components (Figure 37). First, online model estimation is used to periodically estimate the power control and interference models. Second, traffic snooping is used to snoop the ongoing traffic to identify the transmission links. Third, the concurrency check is used to check if the pending data block is transmitted simultaneously with the ongoing traffic according to the interference models. Fourth, interference assessment is used to avoid the primary interference caused by two nodes, which are intended to send the data to the same receiver and for obtaining the interference level information at the intended receiver, which enabling link estimation. Fifth, throughput prediction is used to get the estimated throughput of concurrently transmitting link and sixth, concurrent transmission engine is the most important part of the C-MAC as it coordinates with the other components during their operations.

C-MAC performs one traffic snooping and exchange of RTS/CTS for a block of the packet, while the clear channel assessment (CCA) which was used in B-MAC to sense the channel is completely removed. C-MAC is compared with B-MAC while the sleep mode is disabled in B-MAC to gain high-throughput when nodes are actively communicating. C-MAC performs well as compared to the B-MAC in terms of throughput, delay, and energy consumption.

Advantages: C-MAC is reliable in data-intensive sensing applications. Dynamic power adjustment of the transmitter according to the level of interference of the channel improves the throughput and energy efficiency of the network for high data traffic. C-MAC block-based communication mode enables multiple nodes to transmit concurrently within the interference range of each other and reduces the overhead of channel assessment.

DisAdvantages: C-MAC obtains high-throughput by not letting the node sleep, resulting in high energy consumption and is not suitable for low data traffic.

VIII. CONCLUSION

This paper has presented an extensive overview of energy-efficient MAC protocols for WSNs. We first introduced sensor nodes, WSNs and their applications, followed by a short discussion on the basic characteristics of MAC protocols and the common causes of energy consumption in WSNs. Then, we presented a short discussion on the categories of MAC protocols, followed by a discussion of several

TABLE 2. *(Continued.)* **Comparison of surveyed MAC protocols for WSNs.**

No	MAC	Year	Contention/ Schedule-based	Basic concept	References	Performance Evaluation	Source of Energy Waste				
							Collisions (Receiver)	Idle listening (Receiver)	Overhearing (Receiver)	Over-emitting (Transmitter)	Control packets overheads
14	X-MAC	2006	Asynchronous	Uses strobed short preambles containing receiver's ID and early ACK to indicate receiver is ready for transmission	S-MAC, T-MAC, Wise-MAC, LPL	LPL	short preamble transmission	during wakeup period	when receiving preamble	Short preambles	ACK
15	A-MAC	2007	Synchronous	Similar to S-MAC, nodes with less remaining energy wake up less often to maintain the network lifetime is not exceeded.	S-MAC, D-MAC, ASAP, B-MAC	S-MAC	Broadcast of SYNC and control packets packets	Reduced as network lifetime decreases	DATA period	None	SYNC, RTS,CTS, ACK. Required for synchronisation and collision avoidance
16	C-MAC	2007	Asynchronous	Uses aggressive RTS (similar to X-MAC) for data transmission	B-MAC, S-MAC, T-MAC, D-MAC	B-MAC, S-MAC, 802.11, GeRaf	Between preambles (RTS) and CTS packets	during wakeup period	when receiving preamble	RTS packets (preamble)	Preamble: RTS, CTS
17	Eco-MAC	2007	FDMA/CSMA	Similar to S-MAC, but frequency channel for data transmission is setup during DATA period	S-MAC, T-MAC, Wise-MAC, B-MAC, TDMA, L-MAC, AI-LMAC, FDMA, Z-MAC	S-MAC Z-MAC	Broadcast of SYNC packets, control packets	minimized	minimized, nodes that hear RTS/CTS can go to sleep if not involved in transmission	None	RTS, CTS. Required for synchronisation, random frequency selection, for collision notification, and for collision avoidance
18	H-MAC	2007	TDMA	using hearbeat rhythm as source of time sync in TDMA without distributing timing info	S-MAC, T-MAC, D-MAC, L-MAC, ER-MAC	Not available	None	during resync	None. Each sensor transmit directly to base station	None	Scheduling and resync
19	HyMAC	2007	FDMA/TDMA	Hybrid FDMA/TDMA with zero potential frequency conflict scheduling algorithm.	S-MAC, T-MAC WiseMAC, B-MAC CSMA-MAC TRAMA, LMAC MMSN	MMSN	in contention slots, for broadcast, scheduling purpose	when there is no transmission in its timeslot	None	None	for scheduling purpose
20	PP-MAC	2007	Asynchronous	Similar to X-MAC	B-MAC, Wise-MAC, S-MAC, T-MAC,	B-MAC		during wakeup period	when receiving preamble	Patterned Preamble	Patterned Preamble, ACK
21	RT-MAC	2007	TDMA	centralised scheduling is based on node's position wrt cluster node north	S-MAC, 802.11, WiseMAC, T-MAC, D-MAC	S-MAC, 802.11	None	Sleep when no TX or RX.	None	None	Scheduling
22	TFMAC	2007	FDMA/TDMA	Similar to HyMAC, with distributed time/frequency scheduling	SMAC/AL, TRAMA LMAC, MMSN	-	during contention slots for broadcast, and during contention free period due if more than one node join network at the same time	when there is no transmission in its timeslot, minimized as each node knows other nodes' transmission schedule	None	None	Required to maintain the network, such as during slot assignment
23	DW-MAC	2008	Synchronous	Use one-to-one mapping between data period and sleep period	S-MAC, T-MAC, D-MAC, R-MAC	S-MAC, S-MAC/AL, R-MAC	Broadcast of SYNC packets,		DATA period	None	SCH, ACK. Required to inform desination node about the interval time before it needs to wake up
24	GW-MAC	2008	TDMA	TDMA	CSMA, S-MAC, T-MAC, L-MAC	LMAC, S-MAC	None	Orphaned nodes	minimised due to scheduling	None	Scheduling
25	Optimised MAC	2008	Synchronous	increase duty cycle based on number of queued message in a node's buffer, i.e traffic load	S-MAC, T-MAC	S-MAC, T-MAC	Broadcast of SYNC packets and control packets	DATA period during low traffic	DATA period	when transmitting to nodes with different schedule	SYNC, SYNCrts. Required for collision avoidance
26	Y-MAC	2008	FDMA/TDMA/CSMA	TDMA by scheduling receiver time slot, with channel hopping to reduce latency.	S-MAC, B-MAC, WiseMAC, X-MAC, L-MAC, PEDAMAC, Funneling MAC, Z-MAC, SCP-MAC, MMSN, McMAC	LPL, Crankshaft	transmission of many sender to same receiver node	During broadcast period/receiver's time slot when channel is idle	None	None	Synchronisation. network partition detection

protocols under each category: synchronous, asynchronous, TDMA and FDMA, in depth, emphasizing their strengths and weaknesses. This classification of WSN MAC protocols aims at identifying recent research trends in the design of MAC protocols. We have also presented design trade-offs between some of the MAC protocols with respect to various matrices such as mobility, energy awareness, QoS, scalability and so on. At last, a detailed comparison of MAC protocols for WSNs is given in Table 2 at the end of this paper.

IX. OPEN RESEARCH ISSUE

Several MAC layer protocols have been proposed for WSNs in recent years, but there is not a single protocol that is accepted as a standard. Some common reasons behind this are as follows. Firstly, most of the MAC protocols are application dependent, which means that it is difficult to standardize a MAC protocol for WSNs. Secondly, there is a lack of standardization at lower layers (physical layer) and the (physical) sensor hardware.

Many MAC protocols have been proposed in recent years under the synchronous, asynchronous, TDMA and FDMA categories. Each category has its own advantages and drawbacks. Figure 2 shows the taxonomy of WSN MAC protocols.

Synchronous MAC protocols always suffer from synchronization packets overheads [52], [56]. Nodes can be synchronized easily when they are not mobile but it becomes challenging when they are mobile.

Asynchronous MAC protocols do not require any kind of synchronization but still need to be on periodically with techniques like low power listening (LPL) or preamble sampling to let the receiver know about the incoming packets and sleep most of the remaining time. Asynchronous protocols do not suffer from idle listening and are more flexible to topology changes. However, long preambles cause higher energy consumption and overhearing in non-intended receivers. To overcome the problem, several solutions are proposed such as the use of small preamble, placing of the destination address in short preambles, etc.

TDMA based MAC protocols have a natural advantage of collision-free medium access but suffer from clock drift problems and decreased throughput at low traffic loads due to idle slots. TDMA based MAC protocols also have difficulties like synchronization of the nodes and adaptation to topology changes, exhaustion of battery capacities, broken links due to interference, sleep schedules of relay nodes and scheduling caused by clustering algorithms. Slots should be assigned while considering these problems, but it is also not easy to change the slot assignment in a decentralized environment because all nodes have to agree on the slot assignment.

TABLE 2. *(Continued.)* **Comparison of surveyed MAC protocols for WSNs.**

No	MAC	Year	Contention/ Schedule-based	Basic concept	References	Performance Evaluation	Source of Energy Waste				
							Collisions (Receiver)	Idle listening (Receiver)	Overhearing (Receiver)	Over-emitting (Transmitter)	Control packets overheads
27	SEHM	2008	CSMA/TDMA	Nodes chooses cluster heads (CH) and these CH is responsible to communicate with base station (BS). CH is responsible for intra-cluster communication and inter-cluster communication.	S-MAC,T-MAC, SCP-MAC, B-MAC.	S-MAC	when more than one nodes broadcast in the same time slot	Orphaned nodes	None	None	Cluster formation and maintenance, Scheduling
28	RI-MAC	2008	Asynchronous	Senders use preamble sampling until it hear a becon from sender as a signal to send DATA. Becons transmitted periodaclly by nodes to check if any data is intended for them.	X-MAC, B-MAC, X-MAC-UPMA	X-MAC	When two sender at a time tries to send DATA packets to same receiver.	None	Very less but in *Dwell time*	Long Preamble	Long Preamble by sender and becons in receiver side
29	W-MAC	2009	Synchronous	Similar to A-SMAC in term of synchronization idea and TMAC by utilizing the FRTS. Divided the network in to concentric circles and uses NodeTag for each node.	S-MAC, T-MAC, PAMAS	A-SMAC	Broadcast of SYNC and control packets packets	during wakeup period	DATA period	None	SYNC, RTS,CTS, ACK. Required for synchronisation and collision avoidance
30	NRT-MAC	2009	Synchronous	Based on the idea of S-MAC. Instead of using the back-off scheme as in S-MAC it is using feedback approach as a medium access strategy	S-MAC, T-MAC, D-MAC, VTS, I-EDF, PR-MAC, RRMAC	S-MAC, T-MAC, VTS	Minimized because of using the feedback based medium access strategy	During wakeup period	DATA period	(CC) Control packet	SYNC: sor synchronization RTS,CTS, ACK and CC for collosion avoidance
31	CBTW-MAC	2009	TDMA	Nodes assigned slots is only utilized for receiving and transmitting the DATA otherwise keep the radio off to avoid idle listening.	TDMA-W, S-MAC,D-MAC	TDMA-W, S-MAC	when more than one nodes broadcast in the same time slot	While parents node wait for data from their child's nodes	None	None	Cluster formation and maintenance, Scheduling
32	C-MAC	2009	FDMA/CSMA	Concurrent wireless channel access based on the empirical power control and physical interference model	B-MAC, S-MAC,T-MAC, WiseMac, TRAMA, DCQS, DRAND, SCP and Funneling-MAC	B-MAC	transmission of many sender to same receiver node	during transmission period, snooping on idle channel	snooping on busy channel	None	During frequency assignment
33	AS-MAC	2010	Synchronous	Nodes' active duration is adaptive to traffic load by adjusting the length of Reserved Active Time (RAT) in an operational cycle.	S-MAC, DW-MAC	DW-MAC	Broadcast of SYNC packets,	While father nodes wait for coming packets	RAT period	None	SCH, ACK. Required to inform desination node about the interval time before it needs to wake up
34	BEAM	2010	Asynchronous	BEAM defines two operation modes, i.e., *Preambles* can be sent with/without payload. Receivers' sleep time is depent on payload size.	S-MAC, B-MAC, Wise-MAC, X-MAC	X-MAC	short preamble transmission	during wakeup period	when receiving preamble	None	Early ACK and ACK
35	EM-MAC	2011	Asynchronous	EM-MAC ultilzes the multiple orthogonal radio channels. The sender precicates receiver's wake-up time and channel for transmission.	MMSN, TMMAC, and PW-MAC	Y-MAC, PW-MAC	Nodes waking up at the same time send the wak-up beacon	None	Wake-up beacon	None	Wake-up beacon and ACK

FDMA based MAC protocols provide the collision-free medium, but they require additional costly circuitry to dynamically communicate with different radio channels. Usage of these protocols in sensor networks increases the cost of nodes, which contradicts with the objective of wireless sensor network systems.

CDMA based MAC protocols can also provide the collision-free medium, but their high computational requirements do not meet the objective of wireless sensor networks. Therefore, we have not discussed such techniques in our survey.

Hybrid MAC protocols utilize the combined strengths of scheduled and unscheduled MAC protocols. These protocols avoid the weaknesses of other protocols and better address the special requirements of WSN MAC protocols. The main advantage of hybrid protocols is their ease and rapid adaptability to traffic conditions, saving a large amount of energy.

A single MAC protocol cannot address all these issues. There is always a tradeoff between energy efficiency, throughput, and delay. With active research pursued in the field by researchers across the world, better MAC protocols are likely to be proposed in near future.

For IoT applications, protocols such as IEEE 802.15.4 and IPV6 have been combined to work seamlessly with the Internet. The IEEE 802.15.4e MAC is a suitable match for a wider range of applications. A few researchers have worked on specific scenarios that have proved to be more effective than the original standards. It is possible to combine different technologies to improve them for a special application or QoS requirement. Recently, researchers have been focusing on improving the standard by adding the additional enhancements to the existing MAC protocol, e.g., EFastA, ELIPDA, Adaptive TSCH, MA-LLDN, but there are still several genuine concerns over the safety and security aspects of the communication.

Though, for a wide range of applications IEEE 802.15.4e is most suited, there are concerns on the lack of implementation and hardware availability. Hardware platforms are required to support a standard and to promote the faster adoption of technology. In WSN, IEEE 802.15.4 has been very successful due to its availability on the Commercial Off The Shelf (COTS) technology. Also, it has been a base standard for several protocols such as ZigBee, 6LoWPAN and wirelessHART. To promote the IEEE 802.15.4e as a standard, a significant effort is needed to develop hardware based on this standard. Apart from hardware, simulations are also needed to explore and understand the behavior of the technology.

TABLE 2. ***(Continued.)*** **Comparison of surveyed MAC protocols for WSNs.**

36	PRIMA	2011	TDMA/CSMA	PRIMA is composed of a clustering stage and a channel access stage. The channel access stage is a hybrid of TDMA and CSMA.	EQ-MAC, Q-MAC	Q-MAC	Control messages, and broadcast of SYNC packet	While CH node wait for data from reachable non-CH nodes	None	None	Cluster formation and maintenance, Scheduling
No	**MAC**	**Year**	**Contention/ Schedule-based**	**Basic concept**	**References**	**Performance Evaluation**	**Source of Energy Waste**				
							Collisions (Receiver)	**Idle listening (Receiver)**	**Overhearing (Receiver)**	**Over-emitting (Transmitter)**	**Control packets overheads**
37	PW-MAC	2011	Asynchronous	Senders can predict the wakeup time of receivers based on the parameters received from receivers through beacons, so as to mitigate idle listening and minimize the energy consumption.	Wise-MAC, RI-MAC, X-MAC	Wise-MAC, RI-MAC, X-MAC	Nodes waking up at the same time send the wake-up beacon	None	Wake-up beacon	None	Wake-up beacon and ACK
38	RMAC	2012	TDMA	Receiver nodes assign the timeslots to their sender nodes, thus eliminating possible channel contention and packet collision. RMAC introduces timeslot stealing scheme to reuse the timeslot when it is available.	S-MAC, Z-MAC, TRAMA, Sender-MAC	Sender-MAC	None	During the wakeup time of the receivers when no transmission from assigned sender nodes.	Seconderay senders overhear the transmission from primary senders.	None	HELLO, REQUEST, and ACK message
39	Queen-MAC	2012	TDMA	Nodes are grouped according to their hop distance between the sink. Queen-MAC allows nodes that need to exchange data, to be awake at the same time slot.	QMAC, PW-MAC, TMCP, EM-MAC, C-MAC, MMSN	QMAC, TMCP	Nodes in one group transmit to the same/ common forwarders at the same time.	During the wakeup time of possiable forwarders when no data is sent to them.	The possiable forwarders may overhear data that are not sent to them	None	Control packets *hop-notify*, are sent by the sink node to inform other nodes the information of group id and frequency list
40	AS-MAC*	2013	Asynchronous	AS-MAC schedules the wakeup time of node asynchronously with neighour nodes to avoid overhearing and reduce energy consumption. It also employs ACK upon data reception to support reliable data delivery.	B-MAX, X-MAC, SCP-MAC	CSMA, SCP-MAC	A sender performs backoff for collision avoidance when it losts the channel contention.	During a nodes waits for the ACK, but the data is not successfully delivered.	None	None	HELLO and ACK message
41	CL-MAC	2013	Synchronous	A cross-layer design to schedule the multiples flows packets through multi-hop transmission at a single cycle with the consideration of the pending packets from the routing layers.	R-MAC, LAS-MAC, DW-MAC, BulkMAC, and AM-MAC	RMAC, DW-MAC, and BulkMAC	None	Nodes closer to the destination nodes have longer waiting period.	Nodes may overhear the flow setup packets (FSP).	None	Flow Setup Packet (FSP) and early ACK
42	CR-WSN MAC	2014	Asynchronous	CR-WSN is designed for WSNs with congnitive radio enabled. Nodes can opportunistically access to different channels. Short preambles are transmitted using control channel, and data transmission uses the common channel between senders and receivers.	MAMAC, Y-MAC, and C-MAC	MAMAC	None	Receivers listen to the control channel to receive the short preambles with indication of the destination.	None	Short preambles	Short preambles and data ACK

TABLE 2. ***(Continued.)*** **Comparison of surveyed MAC protocols for WSNs.**

43	RIX-MAC	2014	Asynchronous	RIX-MAC is a receiver -initiated approach that allows senders to predict the wakuptime of receivers. It also introduces back-off time to mitigate collision.	B-MAC, X-MAC, PW-MAC, and RI-MAC	X-MAC and PW-MAC	When multiple nodes send a message to one receiver	During the backoff time of senders, receivers are idle listening	When multiple nodes have data to send to the same receiver, they wake up at the same time and overhear each other.	None	Short preamble and early ACK
44	BN-MAC	2015	Synchronous	BN-MAC ultizes intra-semi-synchronized scheme for transmission within a region, and uses inter-synchronized scheme for transmission between different regions.	X-MAC, Z-MAC, MS-MAC, SPEC-MAC, MA-MAC, ADC-MAC, MobiSense, ME-MAC	X-MAC, Z-MAC, MS-MAC, A-MAC, ADC-SMAC, MobiSense	Transmission within a region with intra-semi-sychronized scheme.	None	Transmission within a region with intra-semi-sychronized scheme.	None	HELLO message and Boarder Node indication signal (BNIS)
No	**MAC**	**Year**	**Contention/ Schedule-based**	**Basic concept**	**References**	**Performance Evaluation**	**Source of Energy Waste**				
							Collisions (Receiver)	**Idle listening (Receiver)**	**Overhearing (Receiver)**	**Over-emitting (Transmitter)**	**Control packets overheads**
45	BEST-MAC	2016	TDMA	BEST-MAC introduces tiny time slots to adaptively handle traffic in clustering based network. In addition, it also designs the short addressing scheme (1 bit) to uniquely identify a node,	S-TDMA, DGRAM, IH-MAC, BS-MAC, E-TDMA and BMA-RR	E-TDMA and BMA-RR	None	Coordinator remains in idle listening during the whole control period.	Coordinator may overhear other nodes' transmission during its wake up time.	None	CH_ANN, JOIN_REQ, CS_ALLOC, ADS_ANN messages
46	FTA-MAC	2016	Asynchronous	In FTA-MAC, receivers send wakeup beacon to initiate the communication. The wake up interval is dynamicly adjusted to adapt to the estimated traffic with TSR.	RI-MAC, PW-MAC, TDA-MAC and RICER	TDA-MAC and RICER	Senders wakup at the same time and send the wakeup beacon.	During the wakeup period.	None	None	Wakeup beacon and ACK message
47	PRIN	2016	Synchronous	PRIN makes use of priority queues for data with different QoS requirements. The sample inter-arrival rate of data varies.	S-MAC, T-MAC, DB-MAC, Q-MAC and WiseMAC	S-MAC and T-MAC	When senders transmit at the same time.	When other node wait for the coming packets.	DATA period	None	ACK

ABBREVIATION USED

ABP	Ambulatory Blood Pressure.
ACK	Acknowledgement.
ADB	Asynchronous Duty-cycle Broadcasting.
AMAC	Adaptive Multiple Access Control.
AP	Access Point.
AS-MAC	Adaptive Scheduling MAC.
AS-MAC∗	Asynchronous Scheduled WSN MAC.
BACK	Broadcast Acknowledgement.
BEAM	Burst-aware Energy-efficient Adaptive MAC.
BEST-MAC	Bitmap-assisted efficient and scalable TDMA-based MAC.
B-MAC	Berkeley Medium Access Control.

BMMM	Broadcast Mode Multicast MAC.
BMW	Broadcast Medium Window.
BN-MAC	Boarder Node-MAC.
BS	Base Station.
BSMA	Broadcast Support Multiple Access.
BSN	Body Sensor Network.
CBR	Constant Bit Rate.
CBTW-MAC	Clustering Based Time-division-multiple-access Wakeup Medium Access Control.
CC	Clear Channel.
CCA	Clear Channel Assessment.
CCC	Clear Channel Counter.
CCF	Clear Channel Flag.
CH	Cluster Head.
C-MAC	Convergent Multiple Access Control.
CR-SLF	Channel reuse-based Smallest Latest-start-time First.
CR-WSN	MAC Spectrum-aware multichannel asynchronous MAC.
CL-MAC	Cross-Layer MAC protocol.
CSMA	Carrier Sense Multiple Access.
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance.
CTS	Clear to Send.
DCF	Distributed Coordination Function.
DDB	Dynamic Delay Broadcasting.
DDT	Data Distribution Table.
DFD	Dynamic Forwarding Delay.
DIFS	DCF Inter-Frame Space.
DK	Development Kit.
D-MAC	Dynamic Medium Access Control.
DS-MAC	Dynamic Sensor Medium Access Control.
DSSS	Direct Sequence Spread Spectrum.
DW-MAC	Demand Wakeup Multiple Access Control.
ECG	Electrocardiogram.
ECN	Explicit Contention Notification.
ECS	Efficient Counter-Based Broadcast Scheme.
EEDO-MAC	Energy Efficient and Delay Optimized Multiple Access Control.
EFA	Exclusive Frequency Assignment.
ER-MAC	Energy and Rate-based Multiple Access Control.
EM-MAC	Efficient Multichannel MAC.
FTA-MAC	Fast Traffic Adaptive Energy-efficient MAC.
FDMA	Frequency Division Multiple Access.
FFT	Fast Fourier Transform.
FRTS	Future Request to Send.
FTP	File Transfer Protocol.
GPS	Global Positioning System.
GSM	Global System for Mobile communications.
GUI	Graphical User Interface.
GW-MAC	Glacs-Web Medium Access Control.
HCL	High Contention Level.
Hy-MAC	Hybrid Multiple Access Control.
IC	Integrated Circuit.
IEEE	Institute of Electrical and Electronics Engineers.
I-EDF	Implicit Earliest Deadline First.
I/O	Input/ Output.
ITU	International Telecommunications Union.
L	Listening.
LCL	Low Contention Level.
LEACH	Low-Energy Adaptive Clustering Hierarchy.
LPL	Low Power Listening.
LPM	Low Power Mode.
LPRF	Low Power RF.
MAC	Medium Access Control.
MACA	Multiple Access with Collision Avoidance.
MANET	Mobile Ad-hoc Network.
MCBR	Multicast Constant Bit Rate.
MCDS	Multicast Connected Dominate Set.
MCU	Micro Controller Unit.
MEMS	Micro-Electro-Mechanical Systems.
MF-MAC	Micro-Frame Multiple Access Control.
MMSN	Multi-frequency Multiple-access-control for Sensor Network.
NAV	Network Allocation Vector.
NP	Neighbour Protocol.
NRT-MAC	Novel Real Time Multiple Access Control.
NS-2/NS-3	Network Simulator-2/ Network Simulator-3.
OFDM	Orthogonal Frequency-Division multiplexing.
OFDMA	Orthogonal Frequency-Division Multiple Access.
O-MAC	Optimized Multiple Access Control.
OP	Opportunistic Flooding.
PAN	Personal Area Networks.
PCF	Point Coordination Function.
PCG	Phonocardiography.
PDR	Packet Delivery Ratio.
PIFS	PCF Inter-Frame Space.
PP-MAC	Patterned Preamble Multiple Access Control.
PR-MAC	Path Oriented Real-time Multiple Access Control.
PRIMA	Energy efficient priority based MAC.
PRIN	Priority-based energy-efficient MAC.
PW-MAC	Predictive-Wakeup MAC.
QoS	Quality of Service.
Queen-MAC	Adaptive energy-efficient MAC protocol.
RAM	Random Access Memory.
RAD	Random Assessment Delay.
RF	Radio Frequency.
RFID	Radio-Frequency Identification.
RDT	Random Delay Time.
RI-MAC	Receiver Initiated Multiple Access Control.
RI-MAC	Random Interference Multiple Access Control.

RIX-MAC	Receiver-initiated MAC based on X-MAC.
RSSI	Received Signal Strength Indication.
RT-MAC	Real-time Medium Access Control.
RTS	Request to Send.
RX	Receive.
S	Sleeping.
SAR	Specific Absorption Rate.
SCH	Scheduling.
SEP	Schedule Exchange Protocol.
SINR	Signal to Interference plus Noise Ratio.
S-MAC	Sensor Medium Access Control.
SYNC	Synchronization.
T	Transmission.
TA	Timeout.
TDMA	Time Division Multiple Access.
TEEM	Traffic Aware Energy Efficient Multiple Access Control.
TF-MAC	Time Frequency Multiple Access Control.
TI	Texas Instruments.
T-MAC	Timeout Medium Access Control.
TMMAC	Energy Efficient Multi-Channel MAC Protocol.
TS	Time Slot.
TX	Transmission.
USB	Universal Serial Bus.
VBR	Variable Bit Rate.
VTS	Virtual TDMA for Sensors.
WLAN	Wireless Local Area Networks.
W-MAC	Wave Multiple Access Control.
WPAN	Wireless Personal Area Networks.
WSNs	Wireless Sensor Networks.
Z-MAC	Zebra Medium Access Control.

REFERENCES

[1] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Comput. Netw.*, vol. 52, no. 12, pp. 2292–2330, 2008.

[2] K. Akkaya and M. Younis, "A survey on routing protocols for wireless sensor networks," *Ad Hoc Netw.*, vol. 3, pp. 325–349, May 2005.

[3] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, 2002.

[4] K. Romer and F. Mattern, "The design space of wireless sensor networks," *IEEE Wireless Commun.*, vol. 11, no. 6, pp. 54–61, Dec. 2004.

[5] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[6] M. Zhao, A. Kumar, P. H. J. Chong, and R. Lu, "A comprehensive study of RPL and P2P-RPL routing protocols: Implementation, challenges and opportunities," *Peer-Peer Netw. Appl.*, vol. 10, no. 5, pp. 1232–1256, 2016.

[7] R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, and D. Culler, "An analysis of a large scale habitat monitoring application," in *Proc. 2nd Int. Conf. Embedded Netw. Sensor Syst. (SenSys)*, Baltimore, MD, USA, vol. 226, Nov. 2004, pp. 214–226.

[8] M. Zúñiga and B. Krishnamachari, "Integrating future large-scale wireless sensor networks with the Internet," Dept. Elect. Eng., Univ. Southern California, Los Angeles, CA, USA, Tech. Rep. CS 03-792, 2003.

[9] A. Kumar, H. Y. Shwe, K. J. Wong, and P. H. Chong, "Location-based routing protocols for wireless sensor networks: A survey," *Wireless Sensor Netw.*, vol. 9, no. 1, pp. 25–72, 2017.

[10] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Commun. Mag.*, vol. 40, no. 8, pp. 102–114, Aug. 2002.

[11] W.-C. Peng, Y.-Z. Ko, and W.-C. Lee, "On mining moving patterns for object tracking sensor networks," in *Proc. 7th Int. Conf. Mobile Data Manage. (MDM)*, Nara, Japan, May 2006, p. 41.

[12] W. Zhang and G. Cao, "DCTC: Dynamic convoy tree-based collaboration for target tracking in sensor networks," *IEEE Trans. Wireless Commun.*, vol. 3, no. 5, pp. 1689–1701, Sep. 2004.

[13] A. Cerpa, J. Elson, M. Hamilton, J. Zhao, D. Estrin, and L. Girod, "Habitat monitoring: Application driver for wireless communications technology," in *Proc. ACM Workshop Data Commun. Latin Amer. Caribbean*, San Jose, CR, USA, 2001, pp. 20–41.

[14] C.-C. Chen and C.-H. Liao, "Model-based object tracking in wireless sensor networks," *Wireless Netw.*, vol. 17, no. 2, pp. 549–565, 2011.

[15] T.-S. Chen, W.-H. Liao, M.-D. Huan, and H.-W. Tsai, "Dynamic object tracking in wireless sensor networks," in *Proc. 13th IEEE Int. Conf. Netw. (ICON)*, Kuala Lumpur, Malaysia, vol. 1, Nov. 2005, pp. 475–480.

[16] A. Milenković, C. Otto, and E. Jovanov, "Wireless sensor networks for personal health monitoring: Issues and an implementation," *Comput. Commun.*, vol. 29, pp. 2521–2533, Aug. 2006.

[17] H. Alemdar and C. Ersoy, "Wireless sensor networks for healthcare: A survey," *Comput. Netw.*, vol. 54, no. 15, pp. 2688–2710, 2010.

[18] P. Kulkarni and Y. Ozturk, "mPHASiS: Mobile patient healthcare and sensor information system," *J. Netw. Comput. Appl.*, vol. 34, no. 1, pp. 402–417, 2011.

[19] A. Kumar and K.-J. Wong, "A variable preamble length-based broadcasting scheme for wireless sensor networks," in *Proc. IEEE 7th Int. Conf. Wireless Commun., Netw. Mobile Comput. (WiCOM)*, Sep. 2011, pp. 1–4.

[20] D. Dan, R. A. Cooper, P. F. Pasquina, and F.-P. Lavinia, "Sensor technology for smart homes," *Maturitas*, vol. 69, no. 2, pp. 131–136, 2011.

[21] N. M. Boers *et al.*, "The smart condo project: Services for independent living," in *E-Health, Assistive Technologies and Applications for Assisted Living: Challenges and Solutions*. Hershey, PA, USA: IGI Global, 2011.

[22] D.-M. Han and J.-H. Lim, "Smart home energy management system using IEEE 802.15.4 and ZigBee," *IEEE Trans. Consum. Electron.*, vol. 56, no. 3, pp. 1403–1410, Aug. 2010.

[23] C. Kaiwen, A. Kumar, N. Xavier, and S. K. Panda, "An intelligent home appliance control-based on WSN for smart buildings," in *Proc. IEEE Int. Conf. Sustain. Energy Technol. (ICSET)*, Nov. 2016, pp. 282–287.

[24] Y. Xu and W.-C. Lee, "Compressing moving object trajectory in wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. Vol., 3, no. 2, pp. 151–174, 2007.

[25] C. Wenjie, C. Lifeng, C. Zhanglong, and T. Shiliang, "A realtime dynamic traffic control system based on wireless sensor network," in *Proc. Int. Conf. Parallel Process. (ICPP)*, Jun. 2005, pp. 258–264.

[26] T. He *et al.*, "VigilNet: An integrated sensor network system for energy-efficient surveillance," *ACM Trans. Sensor Netw.*, vol. 2, no. 1, pp. 1–38, 2006.

[27] L. Selavo *et al.*, "LUSTER: Wireless sensor network for environmental research," presented at the 5th Int. Conf. Embedded Netw. Sensor Syst., Sydney, NSW, Australia, 2007.

[28] N. Xu *et al.*, "A wireless sensor network for structural monitoring," presented at the 2nd Int. Conf. Embedded Netw. Sensor Syst., Baltimore, MD, USA, 2004.

[29] K. Langendoen and G. Halkes, "Energy-efficient medium access control," in *Embedded Systems Handbook*, R. Zurawski, Ed. Boca Raton, FL, USA: CRC Press, 2005.

[30] L. Lin, K.-J. Wong, A. Kumar, Z. Lu, S.-L. Tan, and S. J. Phee, "Evaluation of a TDMA-based energy efficient MAC protocol for multiple capsule networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2011, no. 1, p. 54, 2011.

[31] P. Naik and K. M. Sivalingam, "A survey of MAC protocols for sensor networks," in *Wireless Sensor Networks*, C. S. Raghavendra, K. M. Sivalingam, and T. Znati, Eds. Boston, MA, USA: Springer, 2004, pp. 93–107.

[32] I. Demirkol, C. Ersoy, and F. Alagoz, "MAC protocols for wireless sensor networks: A survey," *IEEE Commun. Mag.*, vol. 44, no. 4, pp. 115–121, Apr. 2006.

[33] K. Kredo, II, and P. Mohapatra, "Medium access control in wireless sensor networks," *Comput. Netw.*, vol. 51, no. 4, pp. 961–994, 2007.

[34] A. Bachir, M. Dohler, T. Watteyne, and K. K. Leung, "MAC essentials for wireless sensor networks," *IEEE Commun. Surveys Tuts.*, vol. 12, no. 2, pp. 222–248, 2nd Quart., 2010.

[35] P. Huang, L. Xiao, S. Soltani, M. W. Mutka, and N. Xi, "The evolution of mac protocols in wireless sensor networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 1, pp. 101–120, 1st Quart., 2013.

[36] M. Zhao, P. H. J. Chong, and H. C. B. Chan, "An energy-efficient and cluster-parent based RPL with power-level refinement for low-power and lossy networks," *Comput. Commun.*, vol. 104, pp. 17–33, May 2017.

[37] R. Oma, S. Nakamura, T. Enokido, and M. Takizawa, "An energy-efficient model of fog and device nodes in IoT," in *Proc. 32nd Int. Conf. Adv. Inf. Netw. Appl. Workshops (WAINA)*, 2018, pp. 301–306.

[38] A. Koren and D. Šimunić, "Modelling an energy-efficient ZigBee (IEEE 802.15.4) body area network in IoT-based smart homes," in *Proc. 41st Int. Conv. Inf. Commun. Technol., Electron. Microelectron. (MIPRO)*, 2018, pp. 0356–0360.

[39] H.-S. Kim, J. Ko, D. E. Culler, and J. Paek, "Challenging the IPv6 routing protocol for low-power and lossy networks (RPL): A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2502–2525, 4th Quart., 2017.

[40] P. C. Bartolomeu, M. Alam, J. Ferreira, and J. Fonseca, "Supporting deterministic wireless communications in industrial IoT," *IEEE Trans. Ind. Informat.*, vol. 14, no. 9, pp. 4045–4054, Sep. 2018.

[41] H. Farag, A. Mahmood, M. Gidlund, and P. Oesterberg, "PR-CCA MAC: A prioritized random CCA MAC protocol for mission-critical IoT applications," in *Proc. IEEE Int. Conf. Commun.(ICC)*, May 2018, pp. 1–6.

[42] D. De Guglielmo, S. Brienza, and G. Anastasi, "IEEE 802.15.4e: A survey," *Comput. Commun.*, vol. 88, pp. 1–24, Aug. 2016.

[43] M. Ojo, S. Giordano, G. Portaluri, D. Adami, and M. Pagano, "An energy efficient centralized scheduling scheme in TSCH networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2017, pp. 570–575.

[44] R. C. A. Alves and C. B. Margi, "IEEE 802.15.4e TSCH mode performance analysis," in *Proc. IEEE 13th Int. Conf. Mobile Ad Hoc Sensor Syst. (MASS)*, Oct. 2016, pp. 361–362.

[45] A. Elsts, X. Fafoutis, J. Pope, G. Oikonomou, R. Piechocki, and I. Craddock, "Scheduling high-rate unpredictable traffic in IEEE 802.15.4 TSCH networks," in *Proc. 13th Int. Conf. Distrib. Comput. Sensor Syst. (DCOSS)*, Jun. 2017, pp. 3–10.

[46] H. Kurunathan, R. Severino, A. Koubaa, and E. Tovar, "IEEE 802.15.4e in a nutshell: Survey and performance evaluation," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1989–2010, 3rd Quart., 2018.

[47] W. Ye and J. Heidemann, "Medium access control in wireless sensor networks," in *Wireless Sensor Networks*, K. Sohraby, D. Minoli, and T. Znati, Ed. Boston, MA, USA: Springer, 2006.

[48] I. E. Lamprinos, A. Prentza, E. Sakka, and D. Koutsouris, "Energy-efficient MAC protocol for patient personal area networks," presented at the 27th Annu. Int. Conf. Eng. Med. Biol. Soc. (EMBS), Sep. 2005.

[49] J. L. Hill and D. E. Culler, "Mica: A wireless platform for deeply embedded networks," *IEEE Micro*, vol. 22, no. 6, pp. 12–24, Nov/Dec. 2002.

[50] A. El-Hoiydi, "Aloha with preamble sampling for sporadic traffic in ad hoc wireless sensor networks," presented at the IEEE Int. Conf. Commun. (ICC), Apr./May 2002.

[51] L. Lin, K.-J. Wong, A. Kumar, S. L. Tan, and S. J. Phee, "An energy efficient MAC protocol for mobile *in-vivo* body sensor networks," in *Proc. 3rd IEEE Int. Conf. Ubiquitous Future Netw. (ICUFN)*, Jun. 2011, pp. 95–100.

[52] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *Proc. 21st Annu. Joint Conf. IEEE Comput. Commun. Societies (INFOCOMM)*, Jun. 2002, pp. 1567–1576.

[53] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A media access protocol for wireless LAN's," presented at the Conf. Commun. Architectures, Protocols Appl., London, U.K., 1994.

[54] *Information Technology—Telecommunications And Information exchange Between Systems—Local And Metropolitan Area Networks—Specific Requirements—Part 11: Wireless Lan Medium Access Control (MAC) And Physical Layer (PHY) Specifications*," IEEE Standard 802.11-1997, 1997, p. i-445.

[55] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *IEEE/ACM Trans. Netw.*, vol. 12, no. 3, pp. 493–506, Jun. 2004.

[56] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," presented at the 1st ACM Conf. Embedded Netw. Sensor Syst. (SenSys), Nov. 2003.

[57] D. T. van and L. Koen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," presented at the 1st Int. Conf. Embedded Netw. Sensor Syst., Los Angeles, CA, USA, 2003.

[58] G. Lu, B. Krishnamachari, and C. S. Raghavendra, "An adaptive energy-efficient and low-latency MAC for data gathering in wireless sensor networks," presented at the Workshop Energy-Efficient Wireless Commun. Netw. (EWCN), Apr. 2004.

[59] C. Suh and Y.-B. Ko, "A traffic aware, energy efficient MAC protocol for wireless sensor networks," presented at the IEEE Int. Symp. Circuits Syst. (ISCAS), May 2005.

[60] C. Suh, Y. M. Song, Y. B. Ko, and W. D. Cho, "Energy efficient & delay optimized MAC for wireless sensor networks," presented at the Workshop 7th Int. Conf. Ubiquitous Comput. (Ubicomp), Sep. 2005.

[61] E.-S. Jung and N. H. Vaidya, "A power control MAC protocol for ad hoc networks," presented at the 8th Annu. Int. Conference on Mobile Comput. Netw. (MOBICOM), Sep. 2002.

[62] S. Du, A. K. Saha, and D. B. Johnson, "RMAC: A routing-enhanced duty-cycle MAC protocol for wireless sensor networks," presented at the 26th IEEE Int. Conf. Comput. Commun. (INFOCOM), May 2007.

[63] Y. Nam, H. Lee, H. Jung, T. Kwon, and Y. Choi, "An adaptive MAC (A-MAC) protocol guaranteeing network lifetime for wireless sensor networks," *Comput. Commun.*, vol. 30, no. 13, pp. 1–7, Sep. 2007.

[64] R. Yadav, S. Varma, and N. Malaviya, "Optimized medium access control for wireless sensor network," *Int. J. Comput. Sci. Netw. Secur.*, vol. 8, pp. 334–338, Feb. 2008.

[65] Y. Sun, S. Du, O. Gurewitz, and D. B. Johnson, "DW-MAC: A low latency, energy efficient demand-wakeup MAC protocol for wireless sensor networks," presented at the 9th ACM Int. Symp. Mobile Ad Hoc Netw. Comput., Hong Kong, 2008.

[66] S. Niafar and H. S. Shahhoseini, "A new sink based energy efficient and delay sensitive MAC protocol for large scale WSNs," in *Proc. Int. Symp. Perform. Eval. Comput. Telecommun. Syst. (SPECTS)*, vol. 41, 2009, pp. 178–184.

[67] B. K. Singh and K. E. Tepe, "A novel real-time MAC layer protocol for wireless sensor network applications," in *Proc. IEEE Int. Conf. Electro/Inf. Technol. (EIT)*, Windsor, ON, Canada, Jun. 2009, pp. 338–343.

[68] Y. Z. Zhao, M. Ma, C. Y. Miao, and T. N. Nguyen, "An energy-efficient and low-latency MAC protocol with adaptive scheduling for multi-hop wireless sensor networks," *Comput. Commun.*, vol. 33, no. 12, pp. 1452–1461, Jul. 2010.

[69] M. S. Hefeida, T. Canli, and A. Khokhar, "CL-MAC: A cross-layer MAC protocol for heterogeneous wireless sensor networks," *Ad Hoc Netw.*, vol. 11, no. 1, pp. 213–225, Jan. 2013.

[70] A. Razaque and K. M. Elleithy, "Low duty cycle, energy-efficient and mobility-based boarder node—MAC hybrid protocol for wireless sensor networks," *J. Signal Process. Syst.*, vol. 81, no. 2, pp. 265–284, 2015.

[71] A. K. Subramanian and I. Paramasivam, "PRIN: A priority-based energy efficient MAC protocol for wireless sensor networks varying the sample inter-arrival time," *Wireless Pers. Commun., J.*, vol. 92, no. 3, pp. 863–881, 2017.

[72] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," presented at the 1st Int. Conf. Embedded Netw. Sensor Syst., Los Angeles, CA, USA, 2003.

[73] A. El-Hoiydi and J.-D. Decotignie, "WiseMAC: An ultra low power MAC protocol for multi-hop wireless sensor networks," presented at the 1st Int. Workshop Algorithmic Aspects Wireless Sensor Netw. (ALGOSENSORS), Jul. 2004.

[74] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," presented at Proc. 2nd Int. Conf. Embedded Netw. Sensor Syst. (SenSys), Baltimore, MD, USA, Nov. 2004.

[75] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-MAC: A short preamble MAC protocol for duty-cycled wireless sensor networks," presented at the 4th ACM Conf. Embedded Netw. Sensor Syst. (SenSys), Nov. 2006.

[76] Texas Instrument. (2007). *2.4 GHz IEEE 802.15.4/ZigBee-ready RF Transceiver*. [Online]. Available: http://focus.ti.com/lit/ds/symlink/cc2420.pdf

[77] Texas Instrument CC2500. *2.4 GHz RF Transceiver*. Accessed: Nov. 25, 2018. [Online]. Available: http://www.ti.com/lit/ds/symlink/cc2500.pdf

[78] XBee/XBee-PRO. *OEM RF Modules*. [Online]. Available: http://www.libelium.com/squidbee/upload/3/31/Data-sheet-max-stream.pdf

[79] A. Bachir, D. Barthel, M. Heusse, and A. Duda, "Micro-frame preamble MAC for multihop wireless sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, vol. 7, Jun. 2006, pp. 3365–3370.

[80] S. Liu, K.-W. Fan, and P. Sinha, "CMAC: An energy efficient MAC layer protocol using convergent packet forwarding for wireless sensor networks," in *Proc. 4th Annu. IEEE Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Netw. (SECON)*, San Diego, CA, USA, Jun. 2007, pp. 11–20.

[81] M. Zorzi and R. R. Rao, "Geographic random forwarding (GeRaF) for ad hoc and sensor networks: Energy and latency performance," *IEEE Trans. Mobile Comput.*, vol. 2, no. 4, pp. 349–365, Oct./Dec. 2003.

[82] M. Zorzi and R. R. Rao, "Geographic random forwarding (GeRaF) for ad hoc and sensor networks: Energy and latency performance," *IEEE Trans. Mobile Comput.*, vol. 2, no. 4, pp. 349–365, Oct./Dec. 2003.

[83] I. Joe and H. Ryu, "A patterned preamble MAC protocol for wireless sensor networks," in *Proc. 16th Int. Conf. Comput. Commun. Netw. (ICCCN)*, Honolulu, HI, USA, Aug. 2007 pp. 1285–1290.

[84] Y. Sun, O. Gurewitz, and D. B. Johnson, "RI-MAC: A receiver-initiated asynchronous duty cycle MAC protocol for dynamic traffic loads in wireless sensor networks," presented at the 6th ACM Conf. Embedded Netw. Sensor Syst. (SenSys), Raleigh, NC, USA, 2008.

[85] M. Anwander, G. Wagenknecht, T. Braun, and K. Dolfus, "BEAM: A burst-aware energy-efficient adaptive MAC protocol for wireless sensor networks," in *Proc. 7th Int. Conf. Netw. Sens. Syst. (INSS)*, Jun. 2010, pp. 195–202.

[86] L. Tang, Y. Sun, O. Gurewitz, and D. B. Johnson, "PW-MAC: An energy-efficient predictive-wakeup MAC protocol for wireless sensor networks," in *Proc. IEEE INFOCOM*, Apr. 2011, pp. 1305–1313.

[87] L. Tang, Y. Sun, O. Gurewitz, and D. B. Johnson, "EM-MAC: A dynamic multichannel energy-efficient MAC protocol for wireless sensor networks," presented at the 11th ACM Int. Symp. Mobile Ad Hoc Netw. Comput., Paris, France, 2011.

[88] Y. Kim, H. Shin, and H. Cha, "Y-MAC: An energy-efficient multi-channel MAC protocol for dense wireless sensor networks," presented at the 7th Int. Conf. Inf. Process. Sensor Netw., 2008.

[89] B. Jang, J. B. Lim, and M. L. Sichitiu, "An asynchronous scheduled MAC protocol for wireless sensor networks," *Comput. Netw.*, vol. 57, no. 1, pp. 85–98, Jan. 2013.

[90] M. Buettner, G. V. Yee, E. Anderson, and R. Han, "X-MAC: A short preamble MAC protocol for duty-cycled wireless sensor networks," presented at the 4th Int. Conf. Embedded Netw. Sensor Syst., Boulder, CO, USA, 2006.

[91] I. Park, H. Lee, and S. Kang, "RIX-MAC: An energy-efficient Receiver-Initiated wakeup MAC protocol for WSNs," *KSII Trans. Internet Inf. Syst.*, vol. 8, no. 5, pp. 1604–1617, Jan. 2014.

[92] Y. Sun, O. Gurewitz, and D. B. Johnson, "RI-MAC: A receiver-initiated asynchronous duty cycle MAC protocol for dynamic traffic loads in wireless sensor networks," presented at the 6th ACM Conf. Embedded Netw. Sensor Syst., Raleigh, NC, USA, 2008.

[93] V.-T. Nguyen, M. Gautier, and O. Berder, "FTA-MAC: Fast traffic adaptive energy efficient MAC protocol for wireless sensor networks," in *Proc. 11th Int. Conf. Cognit. Radio Oriented Wireless Netw. (CROWNCOM)*, Grenoble, France, D. Noguet, K. Moessner, J. Palicot, Eds. Cham, Switzerland: Springer, May/Jun. 2016, pp. 207–219.

[94] M. M. Alam, O. Berder, D. Menard, and O. Sentieys, "TAD-MAC: Traffic-aware dynamic MAC protocol for wireless body area sensor networks," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 2, no. 1, pp. 109–119, Mar. 2012.

[95] A. Jamal, C.-K. Tham, and W.-C. Wong, "Spectrum aware and energy efficient MAC protocol for cognitive radio sensor network," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr./May 2014, pp. 759–764.

[96] R. Kannan, R. Kalidindi, and S. S. Iyengar, "Energy and rate based MAC protocol for wireless sensor networks," *SIGMOD Rec.*, vol. 32, no. 4, pp. 60–65, Dec. 2003.

[97] H. Li and J. Tan, "Heartbeat-driven medium-access control for body sensor networks," in *Proc. 1st ACM SIGMOBILE Int. Workshop Syst. Netw. Support Healthcare Assisted Living Environ. (HealthNet)*, Jun. 2007, pp. 44–51.

[98] S. J. Marinkovic, E. M. Popovici, C. Spagnol, S. Faul, and W. P. Marnane, "Energy-efficient low duty cycle MAC protocol for wireless body area networks," *IEEE Trans. Inf. Technol. Biomed.*, vol. 13, no. 6, pp. 915–925, Nov. 2009.

[99] G. R. Mark, "Clinical electrocardiography and arrhythmias," in *Report submitted at Harvard-MIT Division of Health Sciences and Technology*. MIT OpenCourseWare, 2004.

[100] M. E. Tavel, *Clinical Phonocardiography and External Pulse Recording*, 4th ed. Chicago, IL, USA: Medical Publishers, 1985, p. 448.

[101] P. Verdecchia *et al.*, "Ambulatory blood pressure. An independent predictor of prognosis in essential hypertension," *Hypertension*, vol. 24, pp. 793–801, Dec. 1994.

[102] J. A. Staessen, L. Bieniaszewski, E. T. O'Brien, Y. Imai, and R. Fagard, "An epidemiological approach to ambulatory blood pressure monitoring: The belgian population study," *Blood Press Monit.*, vol. 1, no. 1, pp. 13–26, 1996.

[103] S. Geschwindner, J. F. Carlsson, and W. Knecht, "Application of optical biosensors in small-molecule screening activities," *Sensors*, vol. 12, no. 4, pp. 4311–4323, 2012.

[104] I. Rhee, A. Warrier, M. Aia, M. L. Sichitiu, and J. Min, "Z-MAC: A hybrid MAC for wireless sensor networks," presented at the 3rd ACM Conf. Embedded Netw. Sensor Syst. (SenSys), Nov. 2005.

[105] L. Dippo *et al.*, "Energy-efficient MAC for broadcast problems in wireless sensor networks," in *Proc. 3rd Int. Conf. Netw. Sens. Syst. (INSS)*, Jun. 2006, pp. 1–4.

[106] A. Sahoo and P. Baronia, "An energy efficient MAC in wireless sensor networks to provide delay guarantee," presented at the 15h ACM IEEE Workshop Local Metrop. Area Netw. (LANMAN), Jun. 2007.

[107] Y. Kim, H. Shin, and H. Cha, "Y-MAC: An energy-efficient multi-channel MAC protocol for dense wireless sensor networks," presented at the Int. Conf. Inf. Process. Sensor Netw. (IPSN), Apr. 2008.

[108] G. P. Halkes and K. G. Langendoen, "Crankshaft: An energy-efficient MAC-protocol for dense wireless sensor networks," in *Wireless Sensor Networks* (Lecture Notes in Computer Science: Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), vol. 4373. Berlin, Germany: Springer, 2007, pp. 228–244.

[109] G. P. Halkes and K. G. Langendoen, "Crankshaft: An energy-efficient MAC-protocol for dense wireless sensor networks," presented at the 4th Eur. Conf. Wireless Sensor Netw. (EWSN), Jan. 2007.

[110] A. Elsaify, P. Padhy, K. Martinez, and G. Zou, "GWMAC: A TDMA based MAC protocol for a glacial sensor network," presented at the 5th ACM Int. Symp. Perform. Eval. Wireless Ad Hoc, Sensor, Ubiquitous Netw. (PE-WASUN), Oct. 2007.

[111] J. M. Nasiri, M. Fathy, and M. Soryani, "Enhancement energy efficient TDMA wake up MAC protocol by clustering for wireless sensor networks," presented at the Int. Conf. Adv. Comput., Commun. Control, Mumbai, India, 2009.

[112] Y. Bashir and J. Ben-Othman, "A scalable and energy-efficient hybrid-based MAC protocol for wireless sensor networks," presented at the 3rd ACM Workshop Perform. Monitor. Meas. Heterogeneous Wireless Wired Netw., Vancouver, BC, Canada, 2008.

[113] H. Huang and J. Wu, "A probabilistic clustering algorithm in wireless sensor networks," in *Proc. IEEE 62nd Veh. Technol. Conf. (Fall-VTC)*, Dallas, TX, USA, vol. 3, Sep. 2005, pp. 1796–1798.

[114] A. Varga, "The OMNeT++ discrete event simulation system," in *Proc. Eur. Simulation Multiconf. (ESM)*, Prague, Czech Republic, Jun. 2001, pp. 1–7.

[115] J. Ben-Othman, L. Mokdad, and B. Yahya, "An energy efficient priority-based QoS MAC protocol for wireless sensor networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2011, pp. 1–6.

[116] Y. Liu, I. Elhanany, and H. Qi, "An energy-efficient QoS-aware media access control protocol for wireless sensor networks," in *Proc. IEEE Int. Conf. Mobile Adhoc Sensor Syst. Conf.*, Nov. 2005, p.-191.

[117] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Annu. Hawaii Int. Conf. Syst. Sci.*, vol. 2, 2000, p. 10.

[118] W. L. Tan, W. C. Lau, and O. Yue, "Performance analysis of an adaptive, energy-efficient MAC protocol for wireless sensor networks," *J. Parallel Distrib. Comput.*, vol. 72, no. 4, pp. 504–514, Apr. 2012.

[119] I. Rhee, A. Warrier, J. Min, and L. Xu, "DRAND: Distributed randomized TDMA scheduling for wireless ad-hoc networks," presented at the 7th ACM Int. Symp. Mobile Ad Hoc Netw. Comput., Florence, Italy, 2006.

[120] G. H. Ekbatanifard, R. Monsefi, M. M. H. Yaghmaee, and S. S. A. Hosseini, "Queen-MAC: A quorum-based energy-efficient medium access control protocol for wireless sensor networks," *Comput. Netw.*, vol. 56, no. 8, pp. 2221–2236, 2012.

[121] C.-M. Chao and Y.-W. Lee, "A quorum-based energy-saving MAC protocol design for wireless sensor networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 2, pp. 813–822, Feb. 2010.

[122] S. Ray, I. Demirkol, and W. Heinzelman, "ADV-MAC: Analysis and optimization of energy efficiency through data advertisements for wireless sensor networks," *Ad Hoc Netw.*, vol. 9, no. 5, pp. 876–892, Jul. 2011.

[123] A. N. Alvi, S. H. Bouk, S. H. Ahmed, M. A. Yaqub, M. Sarkar, and H. Song, "BEST-MAC: Bitmap-assisted efficient and scalable TDMA-based WSN MAC protocol for smart cities," *IEEE Access*, vol. 4, pp. 312–322, 2016.

[124] G. Zhou, C. Huang, T. Yan, T. He, J. Stankovic, and T. Abdelzaher, "MMSN: Multi-frequency media access control for wireless sensor networks," presented at the 25th IEEE Int. Conf. Comput. Commun. (INFOCOM), Apr. 2006.

[125] M. D. Jovanovic and G. L. Djordjevic, "TFMAC: Multi-channel MAC protocol for wireless sensor networks," presented at the 8th Int. Conf. Telecommun. Mod. Satell., Cable Broadcast. Services (TELSIKS), Sep. 2007.

[126] M. Salajegheh, H. Soroush, and A. Kalis, "HYMAC: Hybrid TDMA/FDMA medium access control protocol for wireless sensor networks," presented at the 18th Annu. IEEE Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC), Sep. 2007.

[127] *MICAz: Wireless Measurement System*. Accessed: Nov. 25, 2018. [Online]. Available: http://www.openautomation.net/uploadsproductos/micaz_datasheet.pdf

[128] R. S. J. Polastre and D. Culler, "Telos: Enabling ultra-low power wireless research," presented at the 4th Int. Conf. Inf. Process. Sensor Netw. Special Track Platform Tools Design Methods Netw. Embedded Sensors (IPSN/SPOTS), Apr. 2005.

[129] A. Rowe, R. Mangharam, and R. Rajkumar, "FireFly: A time synchronized real-time sensor networking platform," in *Wireless Ad Hoc Networking: Personal-Area, Local-Area, and the Sensory-Area Networks*. Boca Raton, FL, USA: CRC Press, 2006.

[130] H. Zayani and R. B. Ayed, "Eco-MAC: An energy-efficient and low-latency hybrid MAC protocol for wireless sensor networks," presented at the 2nd ACM Int. Workshop Perform. Monit., Meas., Eval. Heterogeneous Wireless Wired Networks (PM2HWN2N), Oct. 2007.

[131] M. Sha, G. Xing, G. Zhou, S. Liu, and X. Wang, "C-MAC: Model-driven concurrent medium access control for wireless sensor networks," in *Proc. 28th IEEE Int. Conf. Comput. Commun. (INFOCOM)*, Rio de Janeiro, Brazil, Apr. 2009, pp. 1845–1853.

ARUN KUMAR received the B.Tech. degree in computer science and engineering from the Institute of Engineering and Rural Technology, Allahabad, in 2006, the M.Tech. degree in computer science and engineering from the National Institute of Technology (NIT), Rourkela, in 2008, and the Ph.D. degree from the School of Computer Engineering, Nanyang Technological University (NTU), Singapore, in 2014. He was a Post-Doctoral Research Fellow at the Institute of Information Science, Academia Sinica, Taipei, Taiwan, from 2014 to 2015. He was also a Research Associate at the Infocomm Centre of Excellence, School of Electrical and Electronics Engineering, NTU. He has been a Research Fellow at the Electrical Machines and Drives Laboratory, Department of Electrical and Computer Engineering, National University of Singapore, Singapore, since 2015. He has been an Assistant Professor with the Department of Computer Science and Engineering, NIT, since 2018. His research interests include wireless sensor networks, ad hoc and mobile networks, Internet of Things/Vehicles, communication algorithms, and computer network analysis.

MING ZHAO received the B.Eng. degree in communication engineering from Tianjin University, China, and the Ph.D. degree from the Department of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. She was a Post-Doctoral Research Fellow at the Smart Mobility Experience Lab, Department of Electrical and Electronic Engineering, Nanyang Technological University. She is currently a Research Scientist with the Institute for Infocomm Research, Agency for Science, Technology and Research, Singapore. Her research interests include the machine-to-machine communications and wireless networking protocols with a special focus on the routing techniques for low-power and lossy networks and vehicular communications and V2X technologies.

KAI-JUAN (STEVEN) WONG received the bachelor's degree (Hons.) in computer engineering from Nanyang Technological University (NTU), receiving a Compaq Gold Medal for overall proficiency in his field as well as an NTU Alumni Prize for academic excellence, and the Ph.D. degree from The University of Edinburgh, U.K. He was with the Computer Communications Division, School of Computer Engineering, NTU, from 2007 to 2012. He is currently an Associate Professor and the Program Director at the Singapore Institute of Technology (SIT), where he spearheaded one of SIT's flagship degree programs in software engineering since 2014. He has published nearly two dozen academic papers, and has worked as an engineering consultant to companies in Singapore. His research interests include wireless sensor networks, mobile ad hoc networks, and embedded systems. He received the Nanyang Excellence in Teaching Award in 2012.

YONG LIANG GUAN received the B.E. degree (Hons.) from the National University of Singapore and the Ph.D. degree from Imperial College London, U.K. He is currently a tenured Associate Professor at the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, where he is also the Head of two industry collaboration labs: NTU-NXP Smart Mobility Lab and Schaeffler Hub for Advanced Research (SHARE). His research interests broadly include coding and signal processing for communication systems, data storage systems, and information security systems. He was an Associate Editor of the IEEE SIGNAL PROCESSING LETTERS. He is an Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. His homepage is at http://www.ntu.edu.sg/home/eylguan/.

PETER HAN JOO CHONG received the Ph.D. degree in electrical and computer engineering from The University of British Columbia, Canada, in 2000. From 2000 and 2001, he was with the Advanced Networks Division, Agilent Technologies Canada Inc., Vancouver, BC, Canada. From 2001 to 2002, he was a Research Engineer at the Nokia Research Center, Helsinki, Finland. From 2009 to 2016, he was an Associate Professor (tenured) with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, where he was also an Assistant Professor from 2002 to 2009. From 2011 to 2013, he was the Assistant Head of the Division of Communication Engineering. From 2013 and 2016, he was the Director of Infinitus, Centre for Infocomm Technology. He is currently a Professor and the Head of the Department of Electrical and Electronic Engineering, Auckland University of Technology, Auckland, New Zealand. He is also an Adjunct Professor with the Department of Information Engineering, The Chinese University of Hong Kong.

• • •