Journal of Distributed Computing and Systems (JDCS)
Vol. 8, Issue 1, 2025, Pages 37-53

A Survey on Medium Access Control Protocols based on Random Access Approach in Wireless Sensor Networks

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Article History:
Received: 12 May 2025
Received in revised form: 26 July 2025
Accepted: 16 August 2025
Available online: 15 September 2025

Abstract

Wireless Sensor Networks (WSNs) represent an advanced generation of wireless networking systems that exhibit numerous applications alongside unique challenges. Among the most important issues associated with WSNs are their constrained resources, necessity for autonomous functionalities, and inherent dynamic nature of their topology. Furthermore, the utmost energy consumption within these networks predominantly occurs during the process of data transmission. Over the recent decade, researchers have been endeavoring to enhance the operational efficiency of these networks through various strategies, including the improvement of existing protocols, the introduction of novel protocols, the enhancement of battery capacity, as well as innovations in chip design and radio frequency equipment. Given the various applications and limitations inherent to WSNs, the design of suitable protocols for signaling, Medium Access Control (MAC), and data routing assumes particular significance. Within WSNs, the radio equipment of sensor nodes constitutes the principal component responsible for energy consumption; thus, effective energy management and judicious utilization of radio equipments in WSNs is imperative. Operations at the data link layer, such as MAC control, are dependent on the utilization of the radio equipment. Consequently, the MAC methods employed within WSNs should engage in the organizing and regulating access to the transmission medium while simultaneously ensuring efficient energy consumption. The purpose of this paper is to investigate popular random MAC protocols within WSNs, which will facilitate the potential for their extension, as well as the design and development of new suitable random MAC protocols tailored for WSNs, to energy efficiency and prolonged network lifetime.

Keywords: Wireless Sensor Network (WSN), Communication Protocol, Medium Access Control (MAC), Random MAC Protocol, Random Access Approach.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are either homogeneous or heterogeneous systems comprised of numerous diminutive devices, referred to as sensor nodes, that are responsible for monitoring diverse environments or tracking specific objects; that is, sensor nodes collaborate with one another and integrate their localized data to achieve a comprehensive understanding and global view of the operational environment [1, 2, 3]. Within WSNs, there exist two additional components known as "aggregation points" (i.e., the deployment locations of Cluster-Heads) and "base station" (i.e., the deployment location of the Sink), which typically possess greater resources and capabilities than standard sensor nodes [4, 5, 6]. Cluster-Heads (CHs) are tasked with gathering information from their corresponding sensor nodes, aggregating this data, and subsequently forwarding it to the Sink for further processing [4-7].

Wireless sensor networks are required to function autonomously in an unattended manner for extended periods [1, 2, 4, 5]. The majority of existing WSNs operate with nodes powered by batteries, and in numerous instances, the replacement or recharging of these batteries is unfeasible. Limited energy resources may lead to a diminished operational lifetime, thereby making energy management that effectively reduces energy consumption while maximizing network longevity critically important. The radio equipment represents the most significant energy-consuming component within a sensor node; for this reason, the efficient utilization of radio resources is essential in WSNs. Link layer operations, such as Medium Access Control (MAC), regulate the employment of radio equipment [8-20]. Consequently, in addition to managing and organizing multiple access configurations, MAC methodologies for WSNs must prioritize energy efficiency.

In other terms, constraints such as energy limitations, bandwidth restrictions, low processing capacities [1-7], and excessive energy consumption by radio equipment during data transmission in WSNs result in conditions including delays in accessing the transmission medium, reductions in network longevity, increasing costs associated with the design and implementation of these networks, and additional financial burdens such as the necessity to replace malfunctioning nodes [8-20]. The proposed solution to address this issue involves the design and implementation of suitable, straightforward, and energy-efficient communication protocols such as Medium Access Control (MAC) tailored for WSNs. Consequently, the main issue examined in this paper pertains to the elevated energy consumption attributable to radio equipment during communication and data transmission within WSNs. To mitigate this challenge, it is imperative to familiarize oneself with existing communication protocols, particularly the MAC protocols. Therefore, the purpose of this paper is to engage in a discourse regarding the existing MAC protocols based on random access approach applicable to WSNs; thus, it elucidates several of the most prominent of these protocols, their corresponding characteristics, as well as their principal advantages and disadvantages. This discourse facilitates the potential for their extension, in addition to the design and development of novel random MAC protocols for WSNs. The introduction of suitable random MAC protocols for WSNs contribute to enhanced energy efficiency and an extended network lifetime. Furthermore, the application of the discussed algorithm enables the resolution of energy constraints and data transmission challenges inherent in WSNs.

The subsequent sections of this paper are organized as follows: Section 2 provides an overview on WSNs; Section 3 considers the concept of Medium Access Control (MAC) and its different dimensions in WSNs; Section 4 discusses several of the most recognized random MAC protocols in WSNs; and finally, Section 5 delineates the reached results and prospective future directions.

II. AN OVERVIEW ON WIRELESS SENSOR NETWORKS

Wireless Sensor Networks (WSNs) represent a decentralized and infrastructure-less wireless network architecture characterized by the presence of numerous diminutive sensor nodes in conjunction with the Sink [1-6]. Within these networks, sensor nodes are deployed in high density within the operational environment, and their available resources are notably constrained. WSNs predominantly serve two principal application domains, namely monitoring and tracking [1-7]. In the continuation of this section, the architecture of a sensor node is illustrated (as depicted in Figure 1), alongside a comprehensive overview of the various characteristics of WSNs, including their key attributes, applications, communication architectures, and vulnerabilities (as indicated in Figure 2).

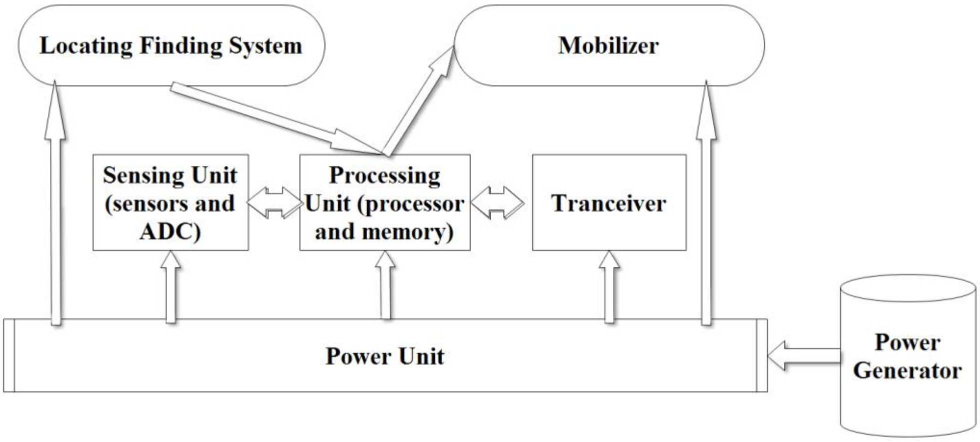

Figure 1. Architecture of a sensor node

Key Attributes

- Infrastructure-less
- Data-centric
- Scalability and distribution of nodes with high density
- Random deployment of nodes
- Dynamic topology
- Self-Configuration
- Application-oriented and environmental adaptability
- Limited resources of nodes: battery supplied energy, processing capability, and storage
- Multi-hop communications
- Necessity of load balancing for providing reliable services
- Wireless, weak, unreliable and unstable links and communications; also, unpredictable environmental interference
- Links failures due to the mobility or failure of nodes
- Low reliability of nodes

Applications (Monitoring and Tracking)

- Environmental
- Industrial
- Military
- Healthcare
- Business and commerce
- Agriculture
- Habitat
- Smart citie
- Smart home
- Smart Zoo
- Transportation
- Energy management
- Water management

Architectural and Structural Features

- Hierarchical or Flat
- Centralized or Distributed
- Homogenous or Heterogeneous
- Static or Dynamic
- Communication architectures: Direct communication, Multi-hop communication (peer to peer), and Clustered communication

Vulnerabilities and Weaknesses

- Phisycal theft, reengineering and replicating of nodes
- Resource severe constraints
- Random deployment
- Security threats and internal attacks
- Unattended operation
- Selfish behaviors of nodes
- Low reliability
- Low fault tolerance and possibility of interruption in active communication
- Cost of nodes' development
- Wireless, unreliable and unstable links and communications
- Links failures, and topology changes, due to the mobility or failure of nodes; it leads to loss of network connectivity, data loss, low efficiency of data transfer, and Quality of Service (QoS) reduction

Figure 2. A comprehensive overview on WSNs: key attributes, applications, architectural and structural features, vulnerabilities and weaknesses

III. MEDIUM ACCESS CONTROL IN WIRELESS SENSOR NETWORKS

The function of the Medium Access Control (MAC) sub-layer within the data link layer is to facilitate the optimal utilization of the communication channel while regulating access to the channel by the nodes [8-20]. In the design of MAC protocols, various factors must be considered, including Quality of Service (QoS), throughput, and energy efficiency; however, these factors often exhibit a trade-off relationship. Therefore, the design of MAC methodologies for WSNs constitutes a significant and multifaceted challenge. The limitations in processing resources and stringent energy consumption constraints necessitate the development of simple and energy-efficient MAC strategies for WSNs. Moreover, given the wide array of applications that utilize WSNs, MAC methodologies must also possess adaptability and flexibility. There exist four primary MAC approaches, as follows [8-20]:

- Scheduling-based MAC approach

The primary benefit of scheduling-based MAC protocols lies in their ability to eliminate collisions, idle listening, and overhearing issues, thereby resulting in a significant reduction of energy wastage. Nevertheless, the cost implications associated with the management and regulation of channel access for nodes at the network level may be excessively burdensome in WSNs that operate under stringent energy limitations. This MAC approach involves the allocation of a dedicated segment of channel access to each node on a permanent basis. Such segments of channel access may manifest as a time slot in TDMA[1]-like protocols, a frequency band in FDMA[2]-like protocols, a code in CDMA[3]-like protocols, or a combination of these elements.

- Synchronous Duty Cycle (SDC) based MAC approach

The objective of this approach is to synchronize nodes according to a unified sleep/wakeup scheduling program; to achieve this, short synchronization messages are periodically exchanged among nodes. The aim of this approach is to coordinate the wake-up and sleep intervals of nodes to facilitate a synchronous duty cycle. Communication is concentrated during designated active intervals, thereby minimizing energy wastage attributable to idle listening. Nodes alternate between concurrent active and inactive intervals. Consequently, this approach necessitates synchronization at the network level.

- Random access MAC approach

In this approach, the sleep/wake-up schedules of nodes are characterized by their independence and lack of synchronization. Each node adheres to its individual schedule, which predominantly involves extended

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[1] TDMA: Time Division Multiple Access
[2] FDMA: Frequency Division Multiple Access
[3] CDMA: Code Division Multiple Access

periods of sleep interspersed with channel sensing at predetermined intervals. A node possessing data awaiting transmission in its packet queue transmits an extended preamble frame prior to data transmission. The time duration of the preamble must suffice to encompass two successive wake-up instances of a potential receiver. The synchronous preamble sampling integrates the previous two approaches. Nodes employ exceedingly brief preambles and necessitate precise synchronization with one another. Thus, random access based protocols can be readily applied to WSNs, demonstrating energy efficiency due to the absence of signaling messages for channel access synchronization. The absence of synchronization indeed results in a reduction of protocol overhead; however, it may significantly expose nodes to challenges such as idle listening, overhearing, and collisions. Various categories of MAC protocols based on random access approach exist, including Preamble Sampling (PS) class, Carrier Sense Multiple Access (CSMA) class, and Multiple Radios class.

- Hybrid MAC approach

This approach represents a synthesis and combination of two or more of the aforementioned MAC strategies.

In continuation, Figure 3 illustrates the different dimensions of MAC protocols in WSNs.

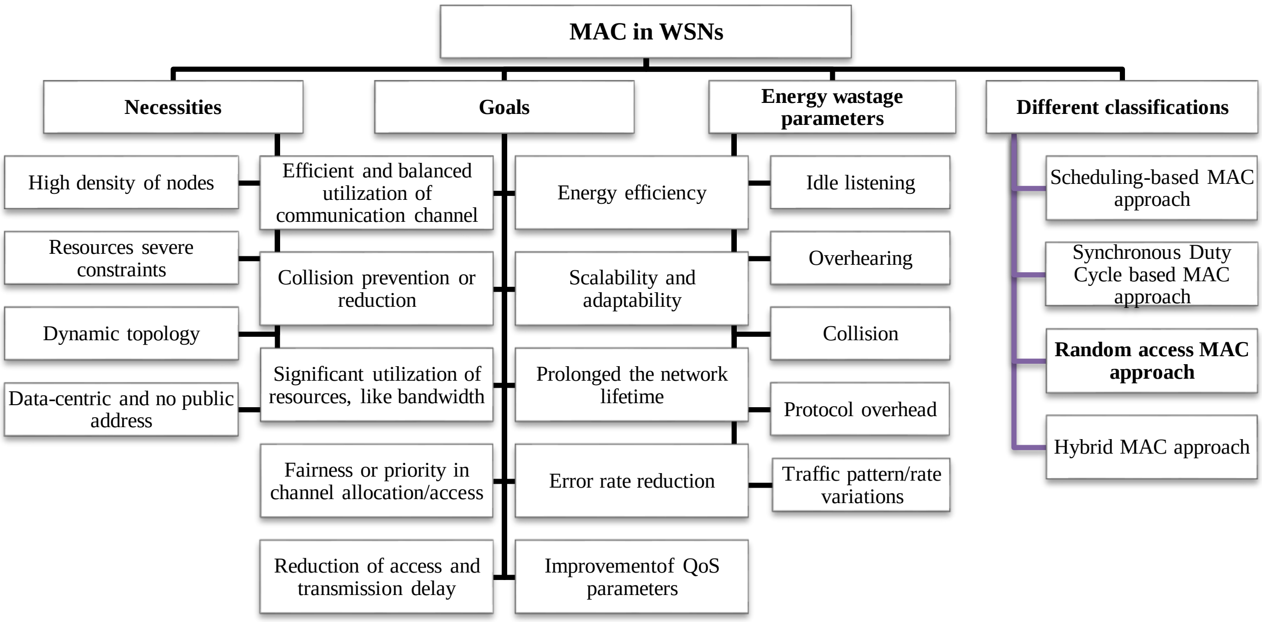

Figure 3. Different dimensions of MAC protocols in WSNs

This paper concentrates on the MAC strategies based on random access approach within WSNs and will discuss its various popular protocols. For each protocol considered, the paper will delineate its characteristics, along with its main advantages and disadvantages.

IV. MEDIUM ACCESS CONTROL PROTOCOLS BASED ON RANDOM ACCESS APPROACH IN WIRELESS SENSOR NETWORKS

The MAC protocols based on random access approach can be readily applied to WSNs, demonstrating energy efficiency due to the absence of signaling messages for channel access synchronization. The absence of synchronization indeed results in a reduction of protocol overhead; however, it may significantly expose nodes to challenges such as idle listening, overhearing, and collisions. Various categories of MAC strategies based on random access approach exist, including [8-20]:

- Preamble Sampling (PS) class
- Carrier Sense Multiple Access (CSMA) class
- Multiple Radios class

A. CSMA/ARC Protocol

In the CSMA/ARC[4] protocol [21], nodes implement an energy-efficient variant of the CSMA protocol that eliminates the necessity for RTS/CTS exchanges. When a node intends to transmit a message, it first monitors the channel for a stochastic duration contingent upon its application layer packet generation period; this approach culminates in reduced back-off times and diminished collision rates. In the CSMA/ARC protocol, nodes aim to promote equity within multi-hop networks; to achieve this, they allocate a fair ratio to both the volume of

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[4] CSMA/ARC: CSMA with Adaptive Rate Control

messages generated by a node and the volume of messages produced by other nodes that necessitate forwarding. Within the CSMA/ARC protocol, nodes employ implicit acknowledgments to conserve energy and minimize overhead; specifically, if a node seeks confirmation regarding the successful delivery of a message to its subsequent hop, it must await the subsequent hop's attempt to relay the message to its own next-hop.

B. *PicoRadio Protocol*

In the PicoRadio protocol [22], nodes use two separate radios, as follows:

- The first radio which it is a very low power single channel radio, for wake-up tone transmission.
- The second radio which it is a multi-channel CDMA radio, for data transmission.

This protocol is organized in two phases, including:

- Setup phase: for orthogonal CDMA code selection; during this phase, nodes randomly choose a dedicated channel among a pool of available channels and then, use a common control channel to exchange their selection. If a node detects a channel collision, it chooses another channel and broadcasts again its choice on the common channel. In the PicoRadio protocol, static nodes quickly converge to a collision free channel assignment. At the end of the setup phase, all nodes are aware of the channels that are controlled by all neighbors.
- Data transmission phase: when the setup phase is ended, all nodes turn off their multi-channel radios and sense the channel by using the low-power radio for a tone to come. In the PicoRadio protocol, tones are unicast; i.e. they can carry the address of the destination. When a node receives a tone destined to it, it turns its multi-channel radio on; it tunes it to the channel corresponding to the sender and receives the data message.

The PicoRadio protocol can support mobile nodes by changing the channel allocation rule, and if mobile nodes are aware of their own mobility. The major issues of this protocol arise from the sensitivity of low-power radio that may result in false positives.

C. *STEM Protocol*

The STEM[5] protocol [23] is a topology management approach which it seeks to increase energy savings in the communications of WSNs by the adoption of the preamble sampling technique and the use of dual radios, including:

- The first radio for signaling
- The second radio for data transmission

In the STEM protocol, nodes that want to initiate communication are called initiator nodes, and nodes that will receive packets are called target nodes. In this protocol, nodes do not need to be synchronized by using the preamble sampling procedure; so, overhead is limited. The STEM protocol consists of two preamble variants, as follows:

- STEM-B: it uses a series of beacons with gaps containing the addresses of the target node.
- STEM-T: it uses tones instead of beacons.

Both variants of STEM send control messages on a dedicated channel to wake up the receiver. STEM-T is a multi-channel precursor of the B-MAC protocol. In the STEM-B, when no packets are to be sent, nodes remain in sleep mode and periodically sample the paging channel by using a low-power radio. If a node detects a beacon announcing a message for it, it sends an ACK to the initiator by using the paging channel; then, it switches its primary radio on to receive data. When the initiator receives the ACK, it also switches its primary radio on and sends data.

D. *Aloha with Preamble Sampling Protocol*

The principal objective of applications within WSNs is the conservation of energy and the enhancement of network longevity. The preamble sampling technique constitutes a particularly compelling methodology, attributable to its markedly low overhead costs and its equitable distribution of energy consumption between sensors and sinks. All inactive receivers cyclically alternate between extended sleep periods (identical duration across all nodes) and brief listening intervals (uniform duration across all nodes). In accordance with the preamble sampling method, receivers are permitted to intermittently transition into idle mode and awaken to assess channel activity. Should a node require the transmission of packets, it initiates its data transmission with designated preamble packets that serve the singular purpose of ensuring that the intended receiver remains alert for data reception. In order to reliably awaken a neighboring node, the transmitter is obligated to send a preamble whose duration sufficiently encompasses the receiver's sleep period. Within this protocol, the preamble sampling strategy was integrated with Aloha and CSMA for sporadic traffic in Ad Hoc WSNs [24].

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[5] STEM: Sparse Topology and Energy Management

E. Sift protocol

The Sift protocol [25] is a MAC protocol for event-driven WSNs; it is a random MAC protocol based on non-persistent CSMA, similar to the IEEE 802.11 access control protocol. The goal of Sift protocol is limiting average latency through low collision probability. In the Sift protocol, nodes choose one transmission slot number within Contention Window (CW) according to a geometrically-increasing probability distribution instead of the common uniform distribution used in IEEE 802.11. Moreover, CW duration is never increased, even if some collisions are detected (in IEEE 802.11 if collisions are detected, the CW size will be increased according to the BEB rule). When a node wants to transmit, it chooses a time slot number k within the range [1, CW] according to an approximation of a geometrically-increasing probability distribution, that depends upon CW and another parameter which it is constant and must be chosen off-line. The use of a non-uniform probability distribution results in low collision and permits to maintain the CW small throughout the entire network lifetime independently of collision occurrence.

F. WiseMAC Protocol

The WiseMAC protocol [26] is a wireless sensor MAC protocol. In this protocol, each node integrates its forthcoming wake-up moment within each acknowledgment (ACK) message that follows data transmission; consequently, all nodes are enabled to ascertain the wake-up timings of their neighbors via a passive mechanism. Whenever a node receives an ACK frame, it updates its local table with the wake-up timings of neighboring nodes to account for clock drift. The WiseMAC protocol delineates a medium access strategy based on preamble sampling, with the improvement that the incidence of overhearing is mitigated through attentiveness and the utilization of information regarding the duty cycle schedule of neighbors at the transmitter side. Within the WiseMAC framework, when a node requires the transmission of data, it possesses knowledge of the exact moment at which the intended receiver will become active. Consequently, instead of transmitting a prolonged and extended preamble, it can commence and initiate the transmission of a significantly abbreviated and shorter preamble immediately prior to the receiver's wake-up moment. In cases where information regarding the subsequent wake-up instant is not available on the sender's side, it resorts to employing a lengthy preamble. The implementation of the WiseMAC technique results in energy savings on both the sender's and receiver’s sides; because the first transmits only when necessary and the latter does not need to remain awake for the entire duration of the (long) preamble before the reception of actual data.

G. B-MAC Protocol

In the context of the B-MAC protocol [27], all devices repetitively engage in a uniform cycle throughout their operational duration: awakening, assessing the channel, and subsequently entering a sleep state. The wake-up schedules of nodes are neither synchronized nor coordinated, indicating that nodes lack awareness of the wake-up schedules of their neighboring counterparts. All nodes within the same network adhere to a common wake-up interval. To effectively awaken the intended receiver, thereby notifying it of a transmission interest for a data frame, each transmitter dispatches an extended advertisement message, referred to as a preamble message. The length of the preamble must be at least equal to the wake-up interval. Upon waking, a node transitions its radio to idle mode and conducts channel polling to identify any radio activity within its proximity. The detection of channel activity is executed utilizing the Clear Channel Assessment (CCA) technique, which involves sampling the measured received power levels and comparing these samples against a predetermined noise floor; if a series of consecutive samples falls below the noise floor, the channel is deemed clear; otherwise, it is considered busy. In the event that the channel is occupied, the radio shifts to receiving mode until the complete reception of both the preamble and the data frames is accomplished. Following the conclusion of the polling period, if the channel is clear and the node does not possess any data messages awaiting transmission in its buffer, it transitions the radio to sleep mode for an extended duration. Should a node intend to transmit a data frame, it must first activate the receiver; thus, it transmits a preamble with a duration that is at least equivalent to the duration of the receiver's sleep period. Subsequent to the transmission of the preamble, the sender immediately transmits its buffered data frame.

In the B-MAC protocol, devices are not required to achieve synchronization; consequently, this results in reduced overhead; however, energy efficiency is also compromised; as the parent node must receive a segment of a lengthy preamble to receive a data frame. Furthermore, the implementation of a long preamble leads to an increase in latency, particularly within multi-hop networks where data frames necessitate relaying to arrive at their ultimate destination. Preamble messages are broadcast messages; therefore, if a node situated near the sender intercepts a preamble, it is unable to ascertain whether it is the designated recipient until both the preamble and data messages are fully received. Thus, the utilization of lengthy broadcast preambles incurs substantial overhearing costs, especially in densely populated networks characterized by a high number of neighboring nodes.

H. B-MAC+ Protocol

The B-MAC+ protocol [28] constitutes an advancement of the B-MAC protocol, yielding notable energy efficiencies. It improves the efficiency of preamble sampling protocols for WSNs. In the B-MAC+ protocol, the long and extended preamble of B-MAC is segmented into sequential "chunks" that incorporate a "countdown" denoting the conclusion of the preamble transmission. Upon the receiver wakes up and detects the countdown packet, it reverts to a sleep state while being poised to enter receiving mode precisely at the moment the data packet is transmitted. Furthermore, the countdown is accompanied by the specification of the receiver's address, thereby ensuring that nodes not engaged in the communication remain in a dormant state until their designated wake-up interval.

I. MFP-MAC Protocol

The MFP-MAC protocol [29] is characterized as a micro frame preamble sampling MAC protocol; its primary objective being the minimization of energy consumption on both the sender and receiver sides. In contrast to the lengthy preambles prevalent in the B-MAC protocol, the sender disseminates brief messages referred to as micro frames, which are interspersed with gaps. Each micro frame encapsulates information concerning the data frame's content, including the intended destination of the data message, the timing of the last micro frame's transmission, and a summary of the data field. When the receiver awakens and acquires a micro frame directed to it, it is informed of the anticipated data transmission timing; thus, it can promptly revert to a sleep state, like to the B-MAC+ protocol. Within the MFP-MAC protocol, upon waking and receiving a micro frame, the receiver is also afforded the discretion to determine its interest in the forthcoming data; for instance, if the announced data constitutes a repetition of a broadcast message previously received, the receiver will return to sleep until the subsequent wake-up interval.

J. CSMA-MPS and X-MAC Protocols

The CSMA-MPS [30] and the X-MAC [31] protocols endeavor to address the overhearing issue that arises from the extended preambles characteristic of the B-MAC protocol. The CSMA-MPS protocol is a CSMA based protocol with minimum preamble sampling; it is an evolution of the STEM and WiseMAC protocols, while the X-MAC protocol is derived from the CSMA-MPS protocol. Given the similarities between these two protocols, the subsequent discussion will provide a detailed exposition of one of them, specifically the X-MAC protocol. The X-MAC protocol is a short preamble MAC protocol for duty-cycled WSNs. Analogous to the B-MAC protocol, the X-MAC protocol mandates that nodes repetitively engage in the same operational cycle throughout their operational lifespan: awakening, monitoring the communication channel, and subsequently entering a sleep state. The distinction between the X-MAC and B-MAC protocols lies in the fact that when a node possesses buffered data for transmission, it emits a sequence of brief unicast preambles interspersed with intervals, rather than transmitting a singular, elongated preamble. During these intervals, the transmitter transitions the radio to an idle state while anticipating the receipt of an acknowledgment (ACK) from the receiver. Upon the awakening of a neighboring node, if it detects a preamble indicating its intended recipient, it returns an ACK to the transmitter, thereby ceasing the series of preambles, which in turn conserves energy for both devices involved. After the reception of an ACK, the transmitter proceeds to send a data frame.

In contrast to the B-MAC protocol, the brief preambles employed in X-MAC are unicast; their design is aimed at mitigating the overhearing impact on neighboring devices. To enhance network capacity relative to the B-MAC protocol, the receiver, after concluding the reception of a data frame, refrains from immediately reverting to sleep mode and instead remains waiting for a potential subsequent data frame. For a transmitter to function as a second sender during this additional back-off period, it must overhear a preamble directed to the same next-hop to which it intends to transmit; upon this occurrence, it stops the transmission of preambles and adjusts its radio to idle mode until an ACK is overheard. Subsequently, it generates a stochastic time value to initiate a back-off timer, at which point it will send data directly (bypassing the preamble). The duration of the back-off timer is sufficiently extended to allow the initial transmitter ample time to complete its transmission. Upon timer expiration, the node executes Clear Channel Assessment (CCA), and if the channel is deemed unoccupied, it sends the additional data. The overhead remains minimal (given that devices are not synchronized); furthermore, the employment of strobed preambles effectively curtails energy expenditure attributable to the overhearing phenomenon, particularly in comparison to the B-MAC protocol.

K. f-MAC Protocol

The f-MAC protocol [32] is a deterministic media access control protocol without time synchronization. In this protocol, initially, each ready message is disaggregated into several small packets of constant size, referred to as framelets, which are transmitted at a specified frequency. Distinct nodes operate at varying frequencies, thereby mitigating collisions and rendering wake-up synchronization redundant. Specifically, in the context of f-MAC protocols, nodes select the quantity of framelets per message and their transmission frequencies in a manner that ensures at least one framelet per message is delivered without experiencing collisions. The f-MAC protocol's primary advantage lies in its guarantee of message delay being unbounded; however, the potential for energy savings is constrained, as each node is required to periodically monitor channel activity and receive framelets.

L. SpeckMAC-D and MX-MAC Protocols

The SpeckMAC-D protocol [33] is a low-power decentralized MAC protocol for low data rate transmissions in specknets. The MX-MAC protocol [34] is a network-aware adaptation of MAC scheduling for WSNs. In the SpeckMAC-D and similarly in the MX-MAC protocols, if a sender wants to transmit a packet to a receiver, it performs a Clear Channel Assessment (CCA) procedure and then, if the channel is clear, it starts repeating the message packet for at least a given duration. When a receiver wakes up, it checks the medium. If it is busy, it listens until it has received a full data packet or until it realizes that it is not the intended destination for the packet.

The SpeckMAC-D protocol is based on the B-MAC and X-MAC protocols, and the MX-MAC protocol is based on the SpeckMAC-D protocol.

M. MH-MAC Protocol

The MH-MAC protocol [35] is a Multimode-Hybrid MAC protocol for WSNs. It is similar to the CSMA-MPS and X-MAC protocols; it uses series of preambles with gaps instead of long preambles as in the B-MAC protocol. It is based on the X-MAC protocol.

N. RI-MAC Protocol

The RI-MAC protocol [36] is a receiver initiated and random interference MAC protocol for WSNs; it is designed for broadcast communication. It uses random slot assignment in each MAC frame, along with knowledge of neighbors’ transmission schedules to mitigate some of the energy wasting problems with existing MAC protocols. The RI-MAC protocol conserves energy, transmits messages fairly among the nodes in the system, and is adaptive to changes in the topology. In the RI-MAC protocol, the communication is initiated by the receiver. In this protocol, nodes periodically wake-up at random time and send a beacon to advertise neighbors that they are ready to receive data. If a neighbor node is awake and it has waiting data to send, it waits a random back-off time to limit the probability of collisions; then, it senses the channel (by CCA procedure) and if it is clear, it transmits its data. Immediately after packet reception, the receiver sends another beacon to acknowledge the correct packet reception. The transmission of the second beacon has also the goal of announcing that the receiver is ready for additional data transmission.

O. Machiavel Protocol

The Machiavel protocol [37] adds mobility support to the B-MAC protocol. In the Machiavel, mobile nodes have higher transmission priority with respect to static nodes. When a static node ends the transmission of a long preamble, it waits a Machiavel Intern Frame Space (MIFS), before sending actual data. If a mobile node overhears a preamble from a static node, it waits until the end of a long preamble and then, it sends data during MIFS period. In the Machiavel protocol, mobile nodes must be conscious that they are mobile.

P. A-MAC Protocol

The A-MAC protocol [38] improves performance of the RI-MAC protocol by introducing auto-ACKs in response to receiver beacons. After auto-ACK transmission, data are sent using a Contention Window (CW) to reduce the collision probability. If multiple senders have messages to send, auto-ACK messages may collide. In the A-MAC protocol, even if auto-ACKs collide, the receiver is able to decode the information and decide to remain awake to receive data. If data messages collide, the sender increments the size of the CW, that will use when the next beacon will be received.

Q. BOX-MAC Protocol

The BOX-MAC protocol [39] is an auto-adaptive MAC for energy-efficient burst transmissions in WSNs. In this protocol, nodes adapt the preamble duration and the wake-up period depending on traffic load. By default, all nodes use strobed preamble sampling as in X-MAC and CSMA-MPS protocols with the wake-up interval equal to preamble duration. After the reception of a message, the receiver assumes that another message may come very soon and it cuts back its wake-up interval by a predefined amount of time; i.e. it will spend less time in sleeping mode. If the sender needs to send another message to the same receiver, it is now allowed to use a shorter preamble series to be sure to wake-up the receiver; thus, it leads to saving energy and time. If the sender has another packet to send to the same receiver, it can use the short preamble. With this procedure each sender stores the preamble duration that must be used to transmit to each neighbor. If any message is received after a time-out, each receiver switches back to the default wake-up interval.

R. AX-MAC Protocol

The AX-MAC protocol [40] is an adaptive polling interval and short preamble MAC protocol. It is an asynchronous protocol which composed of two basic features. First, rendezvous between the sender and the receiver is reached by a series of short preambles. Second, nodes dynamically adjust their polling intervals according to network traffic conditions. Threshold parameters used to determine traffic conditions and adjust polling intervals are analyzed based on a Markov chain. Energy consumption and network latency are also discussed in detail. Simulation results indicate that the AX-MAC protocol is suited to dynamic network traffic conditions and it is efficient in terms of energy consumption and latency.

S. FS-MAC Protocol

The FS-MAC protocol [41] is a fast synchronization MAC protocol in mobile WSNs, which minimizes packet delay with mobility-based sleep-wakeup scheduling using a sleep-wakeup schedule generator and watchdog nodes. Previous MAC protocols for WSNs assume static sensor nodes. They concentrate on energy efficiency, rather than on packet delay. Thus, these MAC protocols are not suitable for the mobile WSN environment. The FS-MAC protocol is a high throughput MAC protocol and CSMA/CA based protocol. Hence, it guarantees collision avoidance.

T. CFMA MAC Protocol

The CFMA[6] protocol [42] is a high throughput, collision free, mobility adaptive and energy efficient MAC protocol for WSNs. It ensures that transmissions have no collisions, and allows nodes to undergo sleep mode whenever they are not transmitting or receiving. It uses delay allocation scheme based on traffic priority at each node and avoids allocating same back-off delay for more than one node unless they are in separate clusters. The CFMA protocol also allows nodes to determine when they can switch to sleep mode during operation. It provides fast association between the mobile node and the cluster coordinator for mobile nodes. The CFMA protocol performs well in both static and mobile scenarios.

U. A+MAC Protocol

To improve the energy efficiency and the transmission performance of a sensor network MAC protocol under time varying traffic conditions, recent researches have adopted a variable duty cycle operation that makes each node dynamically adjust its own wakeup and sleep schedule according to a predefined trigger condition. However, most of the existing protocols still waste energy on a long preamble packet for waking up a receiver or long idle listening for checking potential communications. To address the energy waste problem, this paper introduces a hybrid MAC protocol called A+MAC [43] that exploits a complementary cooperation between CSMA/CA and preamble sampling. In the A+MAC protocol, CSMA/CA is used for carrying out communication processes, and preamble sampling is used for checking potential communications. Therefore, the A+MAC protocol minimizes both idle listening and the length of a preamble packet by exploiting a short preamble that makes nodes check only the event occurrence. It also optimizes control packet formats and eliminates both virtual carrier sensing and a separate clock synchronization period from conventional CSMA/CA based MAC protocols.

V. SR-MAC Protocol

Event detection is one of the major applications of WSNs. Most of existing MAC protocols are mainly optimized for the situation under which an event only generates one packet on a single sensor node. When an event generates multiple packets on a single node, the performance of these MAC protocols degrades rapidly. The SR-MAC protocol [44] is a new synchronous duty-cycle MAC protocol in WSNs, for the event detection applications in which multiple packets are generated on a single sensor node. The SR-MAC protocol introduces a new scheduling mechanism that reserves few time slots during the Sleep period for the nodes to transmit multiple packets. By this approach, the SR-MAC protocol can schedule multiple packets generated by an event on a single node to be forwarded over multiple hops in one operational cycle without collision. The SR-MAC protocol uses event delivery latency (EDL) and event delivery ratio (EDR) to measure the event detection capability.

W. EEMA-MAC Protocol

The EEMA-MAC protocol [45] is a new energy efficient mobility aware based MAC protocol, which work efficiently in both stationary and mobile scenarios with less energy consumption. In this protocol, the member nodes have sleep and awake time same like existing the S-MAC protocol but it expedites the connection setup and efficiency as Cluster-Head (CH) has extended wake up time and less sleep time. This mechanism is effective to avoid frequent disconnection of nodes and performs well in terms of energy consumption, throughput and packet loss as compared with existing protocols.

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[6] CFMA: Collision Free Mobility Adaptive

X. RA-CDMA MAC Protocol

Low-power, cost-effective, and security-conscious WSNs are increasingly becoming ubiquitous within the realm of the Internet of Things (IoT). Within these networks, receiver-assigned code division multiple access (RA-CDMA) [46] presents advantages over extant multiple access techniques. RA-CDMA networks are characterized by their asynchronous operation, robustness against multipath interference, and resilience in the face of collisions. A lightweight MAC protocol is needed to facilitate communication in RA-CDMA networks between low power sensor nodes and access points. This article provides an overview of RA-CDMA and proposes elements of a new MAC protocol that could improve performance of certain WSNs.

Y. EE-DQRA MAC Protocol

The EE-DQRA protocol [47] is an energy-efficient distributed queuing random MAC protocol specifically designed for the scenarios encountered in wireless body sensor networks (BSNs), which employs the principles of distributed queuing to enhance radio channel utilization.

Z. EnRI-MAC Protocol

Energy consumption emerges as the most critical determinant of performance within WSNs. A majority of MAC protocols operate based on a duty-cycle mechanism designed to mitigate idle listening time, which constitutes a substantial fraction of the depletion of sensor node batteries. Numerous conventional MAC protocols concentrate on optimizing unicast traffic performance through duty-cycle methodologies; however, many have neglected to address other traffic categories. The EnRI-MAC protocol [48] represents an advanced receiver-initiated MAC protocol devised to accommodate a spectrum of traffic types within WSNs. It effectively mitigates two significant contributors to energy depletion: duplicated transmissions and retransmissions. Within the EnRI-MAC protocol, the incidence of duplicated transmissions is curtailed by designating a rendezvous time for the reception of broadcast and multicast data, while the probability of retransmission is substantially diminished by significantly lowering the likelihood of collisions.

AA. EH-MAC Protocol

Wireless Sensor Networks are recognized as the predominant technology for a wide array of applications. Investigations into MAC mechanisms have exerted a considerable influence on the advancement of applications, as the MAC layer plays a pivotal role in resource allocation within WSNs. This paper [49] proposes a MAC protocol for WSNs to overcome traffic changes constraints. To accomplish this objective, it employs an elastic hybrid MAC scheme. The primary focus of the developed MAC protocol is the formulation of a medium access scheme that accommodates the diverse quality of service (QoS) parameters requisite for various established traffic types.

BB. DSMAC Protocol

In the Dynamic Sensor MAC (DSMAC) protocol [50], dynamic duty cycle is as a means to enhance the fixed duty-cycle of the S-MAC protocol. The dynamic mechanism of the S-MAC protocol modulates the duty-cycle in accordance with dynamic and real-time utilization and average sleep delay metrics. The proposed topology, characterized by its distributive nature, regulates the scheduling technique for node wakeup time slots and devises an the S-MAC protocol that capitalizes on this topological control to bolster energy efficiency, reduce delay, and adeptly manage spatially-correlated contention. In comparison to the fixed S-MAC protocol, the DSMAC protocol achieves a reduction in energy consumption and demonstrates superior energy-saving capabilities across circular, grid, and random topologies.

CC. SS-MAC Protocol

The SS-MAC protocol [51] constitutes an enhanced hybrid CSMA/TDMA MAC protocol predicated on a sharable slot based MAC algorithm tailored for WSNs exhibiting a cluster tree topology. Through the meticulous design of the operational mechanisms and frame structures, the enhancement of the hybrid CSMA/TDMA and channel-hopping methodologies inherent in IEEE 802.15.4 MAC, alongside the implementation of a sharable slot algorithm for the asynchronous activation of tree nodes and a succinct address strategy for the identification of member nodes, the proposed protocol effectively ameliorates packet delay and throughput while maintaining low collision rates and minimal node energy consumption.

DD. CA-MAC Protocol

The CA-MAC protocol [52] is a collision avoidance MAC protocol specifically designed for clustering underwater sensor networks; the inherent characteristics of underwater acoustic channels, including high latency, limited bandwidth, and energy constraints, pose significant challenges in the design of an underwater MAC protocol, and current MAC protocol designs often neglect the impact of channel interference factors on networking. This protocol initially categorizes users by integrating the channel characteristics of underwater nodes alongside distance measurements between nodes. Subsequently, based on the clustering framework, it regulates transmit power within clusters according to the channel correlation distance measurements between nodes and the communication range of the Cluster Head (CH), thereby mitigating the network's operational lifetime through cumulative reductions in node power consumption. Ultimately, the cluster structure in each cluster is employed to schedule the transmission of member nodes, concurrently reducing energy consumption while achieving multi-node transmission devoid of collisions.

EE. DAWPC-MAC Protocol

To facilitate routing among nodes and/or the base station (BS) within the dynamic and unpredictable underwater environment, a receiver-initiated deep adaptive MAC protocol incorporating power control and collision avoidance, designated DAWPC-MAC [53], has been proposed to confront the challenges posed by interference, collisions, and energy inefficiency. The proposed framework leverages Deep Q-Learning (DQN) to optimize network performance by improving collision avoidance in fluctuating sensor locations, conserving energy in response to varying path loss correlated with time and depth, and minimizing the number of relaying nodes to ensure reliable communication and synchronization. The proposed MAC protocol meticulously considers the dynamic and unpredictable underwater environment, which is influenced by fluctuations in environmental parameters such as temperature (T) relative to latitude, longitude, and depth. Sensor nodes are empowered to adaptively schedule wake-up intervals and efficiently manage transmission power to communicate with other sensor nodes, while a courier node plays a pivotal role in routing for data collection and forwarding.

FF. MOMA-MAC Protocol

The MOMA-MAC protocol [54] represents a multi-objective optimization MAC protocol grounded in multi-agent reinforcement learning methodologies, aimed at enhancing network throughput while concurrently achieving equitable channel allocation and energy efficiency. The MOMA-MAC protocol employs a delay reward mechanism integrated with the Multi-agent Proximal Policy Optimization Algorithm (MAPPO) to formulate a dual reward framework, thereby facilitating agents to collaboratively and competitively optimize the utilization of network resources. Empirical results demonstrate that the MOMA-MAC protocol significantly outperforms conventional MAC protocols and deep reinforcement learning methodologies with respect to throughput, energy efficiency, and fairness in multi-agent environments, thereby exhibiting considerable promise in enhancing communication efficiency and energy management.

V. CONCLUSION AND FUTURE DIRECTIONS

According to the findings of this study, the principal factors contributing to energy wastage in WSNs are enumerated as follows:

- Idle listening: the phenomenon of monitoring and polling the communication channel without receiving any data frame.
- Overhearing: the act of intercepting and receiving a data frame that is destined for another recipient.
- Collision: the potential for frame re-transmissions that may arise when two data receptions coincide temporally.
- Overhead associated with the protocols and the interchange of control packets.
- Variations in the traffic rates or traffic patterns.

Therefore, in the context of channel access management and control, the Medium Access Control (MAC) protocol for WSN must prioritize energy efficiency. To optimize energy consumption, the objective of the devices is to attain low duty cycles; that is, they alternate between sleep and active states. During active intervals, nodes engage in frame exchanges for communication, whereas during sleep intervals, the radio transceiver is deactivated. The challenge faced by MAC protocols lies in the coordination of active intervals such that when a data frame is queued for transmission, both the transmitter and receiver are awakened, engage in communication, and subsequently revert to a sleep state.

Coordinating active intervals within extensive, densely populated, and multi-hop networks constitutes a complex challenge. Existing methodologies predominantly employ four distinct approaches, which include:

- Scheduling-based MAC approach
- Synchronous Duty Cycle (SDC) based MAC approach
- Random access MAC approach
- Hybrid MAC approach

This paper has conducted an examination of the principal contributions of the MAC protocols based on random access approach in WSNs, elucidating their associated characteristics, strengths, and limitations.

In continuation, Table 1 illustrates the prominent random MAC protocols within WSNs, facilitating a comparative analysis based on their characteristics, foundational protocols, released year, and compatibility with mobile operational environments. Furthermore, Table 2 and Figure 4 indicate key statistical information pertinent to this research; this study has evaluated 34 random MAC protocols within WSNs, 15 of which are compatible with mobile operational environments (44.12%); 13 of these protocols are independent and not derived from pre-existing protocols (38.24%); additionally, around 61.76% of the evaluated protocols are extensions inspired by existing protocols.

Table 3 delineates a classification and comparative analysis of random MAC protocols employed within WSNs, predicated on their inherent characteristics. Table 4 and Figure 5 illustrate a statistical evaluation of random MAC protocols utilized in WSNs, emphasizing their attributes; the findings indicate that approximately 17.65% of these random MAC protocols are based on Carrier Sense Multiple Access (CSMA), around 64.70% are founded on Preamble Sampling, and nearly 17.65% are categorized as Multiple Radio and Multi-Channel protocols.

Table 1. A comparison of random MAC protocols in Wireless Sensor Networks

No.	MAC protocol	Basis protocol[7]	Released year	Mobility support
1	CSMA/ARC	Independent	2001	No
2	PicoRadio	Independent	2001	Yes
3	STEM	PicoRadio	2002	No
4	Aloha with Preamble Sampling	Independent	2002	No
5	Sift	Independent	2003	No
6	WiseMAC	Aloha with Preamble Sampling	2003	No
7	B-MAC	Independent	2004	No
8	B-MAC+	B-MAC	2006	No
9	MFP-MAC	B-MAC	2006	No
10	CSMA-MPS	STEM and WiseMAC	2004	No
11	X-MAC	CSMA-MPS	2006	No
12	F-MAC	Independent	2006	No
13	SpeckMAC-D	B-MAC and X-MAC	2006	No
14	MX-MAC	SpeckMAC-D	2007	No
15	MH-MAC	X-MAC	2007	No
16	RI-MAC	Independent	2008	No
17	Machiavel MAC	B-MAC	2009	Yes
18	A-MAC	RI-MAC	2010	No
19	BOX-MAC	X-MAC	2011	No
20	AX-MAC	X-MAC	2011	Yes
21	FS-MAC	CSMA/CA	2012	Yes
22	CFMA	Independent	2013	Yes
23	A+MAC	CSMA with Preamble Sampling	2013	No
24	SR-MAC	Independent	2013	No
25	EEMA-MAC	S-MAC	2018	Yes
26	RA-CDMA	CSMA/CDMA	2019	Yes
27	EE-DQRA	Independent	2020	Yes
28	EnRI-MAC	Independent	2020	Yes
29	EH-MAC	CSMA with Preamble Sampling	2021	Yes
30	DSMAC	S-MAC	2021	Yes
31	SS-MAC	CSMA & TDMA	2024	Yes
32	CA-MAC	Independent	2025	Yes
33	DAWPC-MAC	EE-DQRA	2025	Yes
34	MOMA-MAC	Independent	2025	Yes

Table 2. Statistical information about the random MAC protocols in Wireless Sensor Networks

Property	Total MAC protocols	Frequency of independent protocols	Percentage of independent protocols	Frequency of extended protocols	Percentage of extended protocols	Frequency of mobility support	Percentage of mobility support
	34	13	38.24	21	61.76	15	44.12

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[7] Basis protocol: this feature shows whether the discussed protocol is an independent/basis protocol or an inspired/extended protocol.

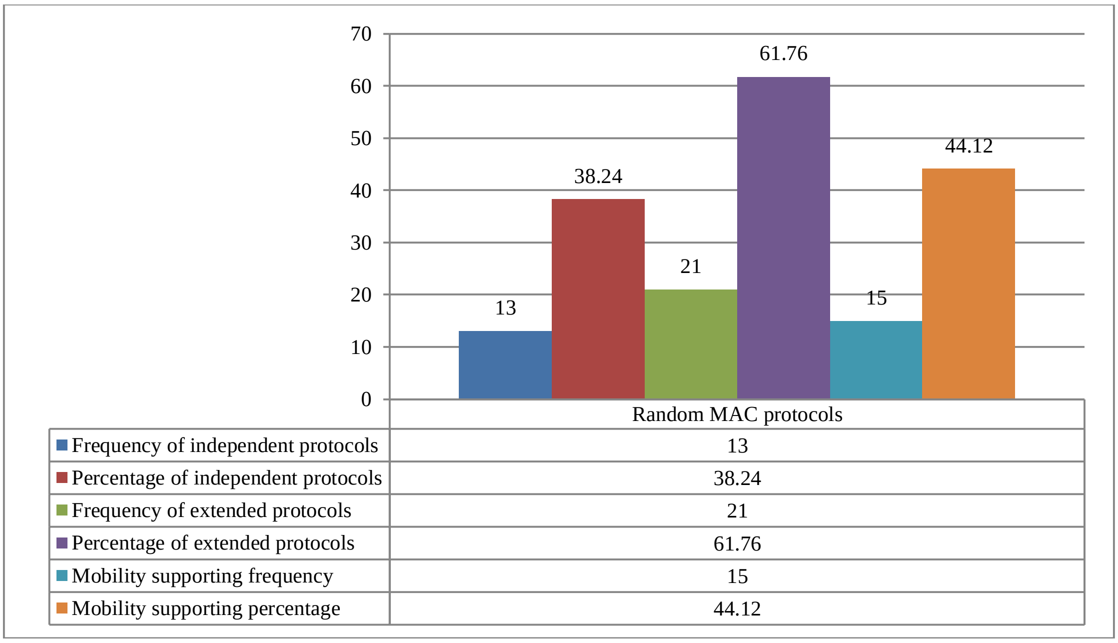

Figure 4. A statistical comparison of mobility and undependability features of random MAC protocols in WSNs (based on frequency and percentage)

Table 3. Classification and comparison of random MAC protocols in Wireless Sensor Networks based on their nature

No.	**MAC protocol**	**Based on CSMA**	**Based on Preamble Sampling (Aloha + CSMA)**	**Based on Multiple Radio and Multi Channels**
1	CSMA/ARC	✓		
2	PicoRadio			✓
3	STEM			✓
4	Aloha with Preamble Sampling		✓	
5	Sift	✓		
6	WiseMAC		✓	
7	B-MAC		✓	
8	B-MAC+		✓	
9	MFP-MAC		✓	
10	CSMA-MPS		✓	
11	X-MAC		✓	
12	F-MAC			✓
13	SpeckMAC-D		✓	
14	MX-MAC		✓	
15	MH-MAC		✓	
16	RI-MAC	✓		
17	Machiavel MAC		✓	
18	A-MAC		✓	
19	BOX-MAC		✓	
20	AX-MAC		✓	
21	FS-MAC	✓		
22	CFMA	✓		
23	A+MAC		✓	
24	SR-MAC			✓
25	EEMA-MAC		✓	
26	RA-CDMA			✓
27	EE-DQRA		✓	
28	EnRI-MAC		✓	
29	EH-MAC		✓	
30	DSMAC		✓	
31	SS-MAC		✓	
32	CA-MAC	✓		
33	DAWPC-MAC		✓	
34	MOMA-MAC			✓

Table 4. Statistical comparison of random MAC protocols in Wireless Sensor Networks based on their nature

No.	**Nature of MAC protocol**	**Frequency of protocols**	**Percentage**
1	Based on CSMA	6	17.65
2	Based on Preamble sampling (Aloha + CSMA)	22	64.70
3	Based on multiple radio and multi channels	6	17.65

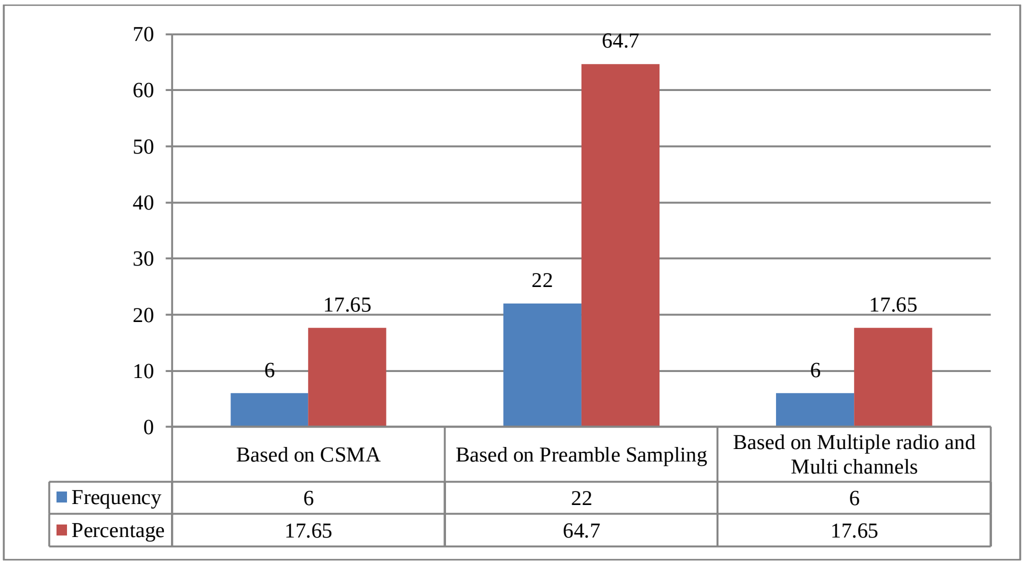

Figure 5. Statistical comparison of random MAC protocols in WSNs based on their nature (in frequency and percentage)

It is hope that this paper proves beneficial in elucidating the MAC protocols based on random access approach within WSNs and paving a pathway for the extension of current protocols or the suggestion of novel random MAC protocols tailored to the distinctive characteristics of WSNs and requirements of each operational environment. Several additional issues warrant further investigation in future research endeavors. Among the most challenging and proposed topics concerning these issues are the following:

- The design and development an energy-efficient and light-weight random MAC protocol for WSNs.
- The presentation of a light-weight error detection and correction algorithm, and its integration within the MAC protocol.
- The suggestion of a light-weight data compression and aggregation algorithm for application prior to accessing the communication channel.
- Conducting a survey on synchronous duty cycle MAC protocols and also, scheduling-based MAC protocols within WSNs.

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How to cite: Hossein Jadidoleslamy, **A Survey on Medium Access Control Protocols based on Random Access Approach in Wireless Sensor Networks**, Journal of Distributed Computing and Systems (JDCS), Vol 8, Issue 1, Pages 37-53, 2025.