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Review Article

SMAC-Based WSN Protocol-Current State of the Art, Challenges, and Future Directions

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Wireless Sensor Networks (WSNS) have become an indispensable tool in this epoch of technological advancements, particularly for progress made in the Internet of things. Wireless sensor nodes are deployed to collect and transmit vital data from the environment to a base station for analysis. Nevertheless, the limited battery power of the sensor nodes is rapidly drained when they stay awake for an extended period. Research has shown that significant sources of energy dissipation of sensor nodes are idle listening, packet collision, control overhead, and overhearing. One optimal solution is employing a low duty cycle mac protocol, particularly the sensor mac (SMAC) protocol. It is essential to have a detailed knowledge of the challenges identified in SMAC and solutions suggested to mitigate these challenges and the future directions. In this paper, we review techniques in SMAC protocols implemented in WSNS. In particular, we provide highlights of recent developments in the schemes used in SMAC for mitigating the challenges in SMAC and present research gaps in SMAC protocol. Finally, we discuss open issues that need to be addressed to advance the design and implementation of SMAC in WSN applications.

1. Introduction

Wireless Sensor Networks (WSNs) are independent, dedicated, and spatially dispersed tiny nodes to sense, collect, and wirelessly transmit data from a specified environment to a central location for analysis [1]. In WSNs, the nodes are autonomous but are designed to cooperate or communicate with each other in their operation [2]. The data collected by sensor nodes from their immediate environment are aggregated and sent to a sink node or base station. The data is processed and analyzed at the base station for relevant stakeholders' decision-making, as illustrated in the architecture shown in Figure 1.

WSNs have found applications in several domains, including healthcare monitoring [3–9], environmental monitoring [10–14], military monitoring [15–17], vehicle monitoring [18, 19], industrial [20, 21], agriculture [22–24], and urban monitoring applications [25]. These numerous application areas have made WSN areas of intense research in wireless communications [26]. Figure 2 illustrates some of the application areas in WSNs.

The tiny low-cost, and battery-powered sensor nodes are the primary drivers behind WSN applications. Sensor nodes can detect and collect data from their deployed environment. Sensor nodes (SNs) typically consist of four major components: a computing unit, a sensor unit, a transceiver unit, and a power unit [27], as shown in Figure 3.

The power unit is the SN's primary energy source, and it is typically powered by batteries such as lithium-ion (Li-ion), lithium-polymer (LiPo), nickel-metal hydride (NiMH), and alkaline [28, 29]. The capacities, voltages, advantages, and disadvantages of the various types of batteries (see Table 1) used in energy-efficient WSN applications have gained attention since batteries are the heart of wireless sensor nodes. Each component unit within the sensor node is powered by the same energy source, the battery. The transceiver unit or communication module in any of its states (i.e. transmission, reception, idle, standby, or sleep

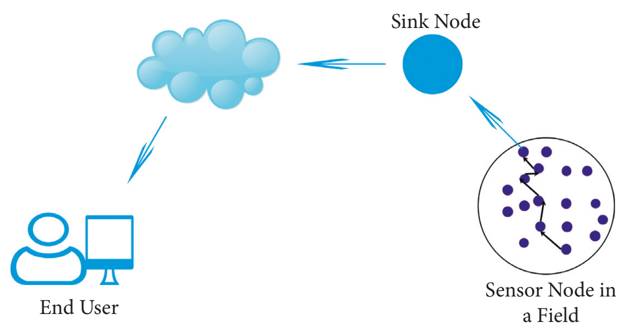

Figure 1: Wireless sensor network architecture.

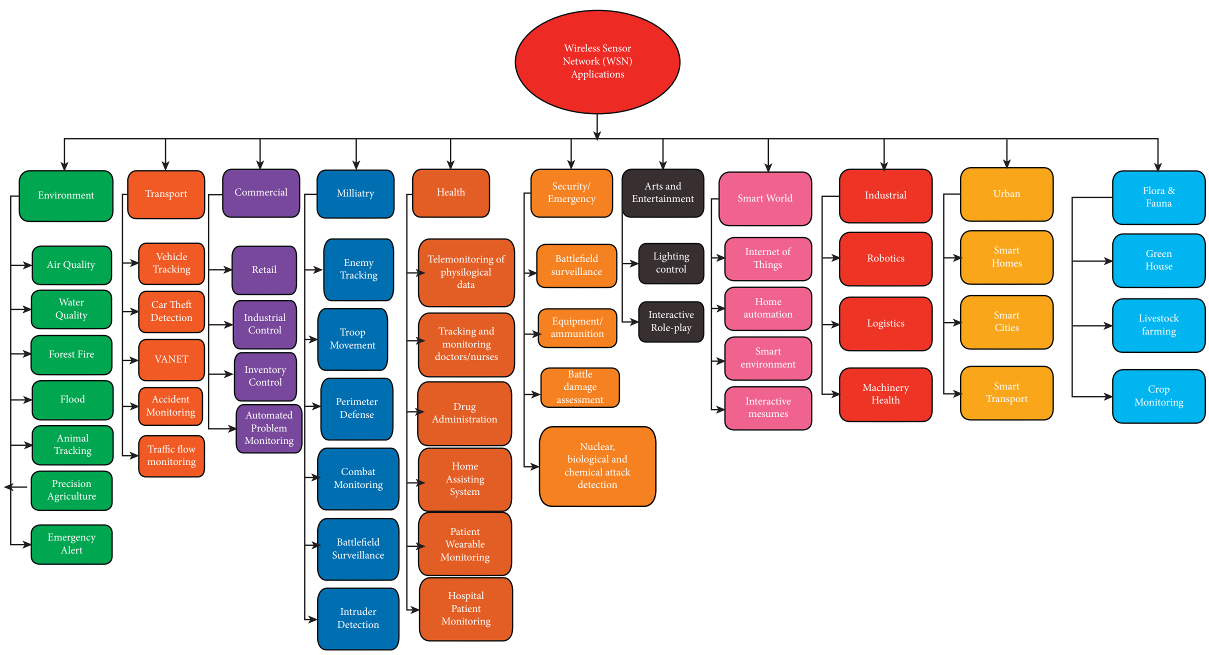

Figure 2: Wireless sensor network applications.

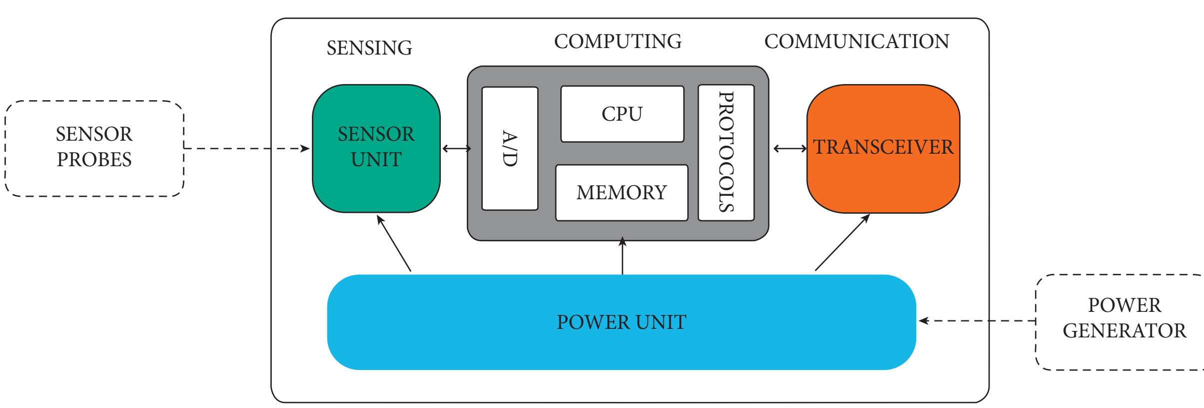

Figure 3: Components of a wireless sensor node.

states) consumes the most battery power when compared to other components such as the processing and sensing units [31, 32]. Data transmission and reception energy costs are proportional to the distance between the source and destination nodes. As a result, the greater the communication distance between source and destination nodes, the greater the energy cost. Narrowband, multipath, low signal-to-noise ratio (SNR), and hidden node interferences cause corrupt frames. The corrupt frames result in layer two retransmissions of corrupted frames, thereby increasing energy

Table 1: Comparison of battery chemistries used in WSNs (adapted from Battery University [30]).

Battery chemistry	Energy density (Wh/kg)	Cycle life	Cell voltage (nominal)	Capacity (mAh)	Operating temperature (°C)	Pros	Cons
Alkaline	80 (initial)	50[3]	1.5	Varies	0 to 65	High energy density, cheap,	Heavily affected by load, heavyweight, high internal resistance
Li-ion	110–160	500–1000[3]	3.6	730	-20 to 60	High energy density, low maintenance, low self-discharge	Expensive, not fully matured
LiPo	100–300	300–500	3.6	930	0 to 60	Flexible form factor, lightweight, more resistant to overcharge	Expensive, low energy density, decreased cycle count
NiMH	60–120	300–500[2,3]	1.25[6]	2500	-20 to 60	Simple storage and transportation, environmentally friendly, less prone to memory	Limited service life, high self-discharge, longer charge time

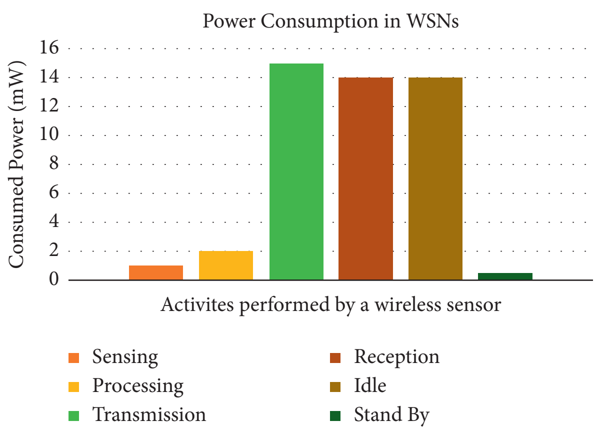

Figure 4: Power consumption in WSNs of a sensor node's components [31].

consumption, whereas shorter transmission and reception distances between nodes consume less energy in WSNs [33–35]. It has been shown that even in the Idle states (when the node is passive and doing 'nothing'), much energy is still expended, especially in event-driven applications, as illustrated in Figure 4. The energy/power consumed by the SN in WSNs during transmission, reception, idle, and standby/sleep states are depicted in Figure 4. The three states, transmission, reception, and idle, will be observed to expend significantly more power than the other states.

Wireless sensor nodes typically share a single communication channel or medium. As a result, if two or more nodes communicate over the channel simultaneously (by transmitting and receiving packets), their data packets may collide or interfere with one another. Packet collisions result in corrupted packets that must be retransmitted. As a result, extra energy is consumed to retransmit the corrupted packets, reducing network lifetime, uptime, and throughput [36]. Overhearing packets waste energy because sensor nodes (SNs) receive packets not intended for them. Energy is also expended by additional data added to the payload, such as control messages broadcasted over the network (i.e. packet control overhead).

Understanding these sources of energy dissipation in WSNs is essential because it enables researchers to propose and implement techniques/algorithms to reduce energy wastage in WSNs and extend network lifetime [37, 38]. As a result, various solutions have been proposed and implemented over the last decade to address this problem. Low Duty Cycle Medium Access Control (LDC-MAC) protocols [39–41], Energy Harvesting (EH) and Wireless Energy Transfer [36, 42–46], and Clustering and Routing Algorithms [47–60] are notable among the approaches. Among these techniques and protocols, LDC-MAC protocols, particularly Sensor Medium Access Control (SMAC), has proven to be the best solution for reducing energy consumption at the MAC layer [40].

The SMAC protocols use energy-saving methods to reduce idle listening, packet collisions, overhearing, and control overhead [61]. However, there may be specific difficulties with adopting SMAC. Challenges posed by SMAC include high energy consumption of border nodes adopting a schedule in a diverse environment [62], fixed duty cycle [63], fixed contention window [64], wasteful idle listening, and latency [65]. There are suggested solutions to improve SMAC's limitations [66–68].

We present an in-depth evaluation of SMAC protocols in WSNs in this article. We provide an overview of synchronous MAC protocols by first describing the available MAC protocols (synchronous, asynchronous, semisynchronous, or hybrid) and the types within each category. We discuss the current challenges, solutions, and future directions for SMAC implementations used for environmental monitoring. To the best of our knowledge, no survey in the literature currently exists that presents the current state of the art, research gaps, and future directions on SMAC in the field of WSN. As a result, this paper attempts to conduct a SMAC survey that captures the current improved SMAC protocols and their limitations, the research pattern and gaps, and propose future research directions.

The rest of the paper is organized as follows: The motivation for SMAC implementation in WSNs is presented in Section 2. Section 3 provides an overview of Medium Access Control (MAC) protocols, emphasising low duty cycle MAC protocols for WSNs. In Section 4, SMAC is discussed. Section 5 discusses improved SMAC propositions and their limitations concerning each identified SMAC limitation; some identified SMAC implementations in WSN applications, challenges, and future research directions for SMAC implementation in WSNs. Finally, Section 6 concludes the paper.

2. Motivation

An essential requirement for Wireless Sensor Networks (WSNs) is that they can operate for extended periods without any intervention. Unfortunately, sensor nodes are battery-powered and hence have limited energy. Over the past few years, various techniques, including energy harvesting, energy transfer, routing, and clustering algorithms, have been employed to improve the energy deficit of sensor node devices. Solar energy is the most widely used and efficient energy harvesting source, requiring installing solar panels made up of numerous solar/photovoltaic (PV) cells to harvest the sun's energy and power the sensor nodes. The PV cells of monocrystalline and polycrystalline materials harvest the sun's energy. The energy is converted into useable electricity to power WSN components. PV is a well-known solar cell with a power density of 15–100 mW/cm^2, a high-output voltage that is only available during the day, and low efficiency during cloudy days. It generates limited energy [69]. As a result, multiple solar panels (monocrystalline, polycrystalline, and thin-film) can be used to generate energy to power sensor nodes [70]. Monocrystalline panels are entirely composed of silicon, polycrystalline panels are composed of melted silicon crystal fragments, and thin-film panels, which are still under development, are composed of various materials, including silicon (8M Solar [71].

The solar panels may be externally mounted or embedded on the enclosure's front containing a sensor node [69, 72–74] in the WSN application. Wireless energy/power transfer (WPT) techniques have been proposed to recharge/transfer power to sensor nodes to maximize network lifetime using branch and bound (B&B) algorithms [75]. Despite researchers' efforts to incorporate WPT into all layers of the OSI reference model in WSN applications, energy efficiency in WSNs remains a critical design issue. To improve on WPT, the hybrid algorithm that combines B&B and beam selection algorithms [75], a collaborative recharging technique to offload recharging workload to local chargers for on-demand and low charging latency [76], an optimized scheduling strategy (EHMDP) that optimizes the scheduling of WPT and data collection of rechargeable wireless sensor networks (RWSNs) [77], single wire transfer method [78], magnetically coupled resonant WPT [79], and static or mobile chargers with the ability to provide stable power for the sensor nodes have been proposed [80–84].

Aside from using energy harvesting and energy transfer to augment the sensor nodes' energy, routing and clustering algorithms are the most utilized techniques to extend the battery lifetime. These algorithms are designed to minimize the energy required to send data throughout the network at the physical link (MAC) and network layers to ensure that the sensor nodes collect sufficient data [36]. In work done by Adu-Manu et al. [36]; the authors highlighted advances in protocol design at the physical, MAC, and network layers. At the physical layer level, power adjustment protocols that seek to enhance the system performance based on link quality parameters [85], multiantennas [86], and joint source-channel coding [87] have been developed. At the MAC layer level, adaptive duty cycle-based [88, 89], CSMA/CA-based [90], and polling-based protocols [91] have been developed over the years. Similarly, routing protocols [92, 93] have been developed at the network layer to minimize the energy consumed by sensor devices.

Researchers have recently focused much attention on an efficient link layer protocol design. The MAC layer protocols are classified into synchronous or asynchronous. Synchronous protocols, such as sensor MAC (SMAC), rely on nodes sharing the sleep schedules. The asynchronous protocols are mainly grouped into transmitter-initiated [94, 95] and receiver-initiated schemes [96–98]. In transmitter-initiated schemes, the nodes wakeup periodically and check for a preamble from the transmitter. In the receiver-initiated scheme, the receiver nodes send periodic beacons to indicate their readiness to receive data [99].

One of the popular protocols at the MAC layer is the SMAC. The SMAC is one of the robust synchronous low duty cycle MAC protocols to mitigate energy dissipation issues at the MAC layer of WSNs. SMAC utilizes periodic listen and sleep, collision and overhearing avoidance, and message passing mechanisms. Several works are proposed in the area of SMAC [62, 64–68, 100–109]. The existing approaches are designed to improve the original SMAC design. Researchers have proposed novel analytical models for SMAC's protocol design and performance analysis [110–114]. Existing reviews in the area of MAC focus on the general overview of MAC protocols for WSNs [115–120], LDC-MAC protocols [121–124], synchronous LDC-MAC [113, 125], asynchronous LDC-MAC [125], mobility-aware MAC protocols [126, 127], receiver-initiated energy harvesting MAC protocols [128], and MAC layer protocols implemented in WSN applications [129–134]. In most of these works, the interest has been in the protocol designs, advantages and disadvantages, challenges, and future directions in WSN.

Over the last decade, a lot of work has been performed in SMAC to solve the limitations of the traditional MAC protocol. Researchers have focused on solving challenges related to (1) High energy consumption of border nodes, (2) Fixed duty cycle, (3) Increased end-to-end delay/latency and packet loss, (4) High control overhead, (5) Unnecessary idle listening, and (7) Fixed contention window or poor backoff in SMAC protocol. Despite the amount of work contributed by researchers in this area, no single publication has surveyed the breakthroughs so far achieved. We are motivated to methodically discuss the innovations and most recent developments made thus far while highlighting the challenges and need for additional work to open up the possibility for other advancements, especially in light of the enormous amount of work done over the years. SMAC serves as the cornerstone for most synchronous LDC-MAC cycle protocols. Although some works have been published, there remain significant limitations stemming from these papers that aimed at improving the protocol considering some implementation challenges of SMAC. A survey on SMAC will bring together the novel developments and the current research pattern, challenges, and future directions for a significant contribution in the area. In WSNs, for monitoring applications, energy-efficient techniques to reduce the energy consumed by sensor nodes to prolong the network lifetime will be beneficial [135].

Given the above, it is essential to clearly define the performance metrics and design requirements that impact WSNs applications using the SMAC protocol given energy limitation in sensor nodes. Hence, in this article, we survey the current state-of-the-art techniques for SMAC for WSNs and the latest protocols and algorithms that optimally minimize the energy to support the application goals and provide continuous environmental monitoring. We also surveyed the novelty of the improved SMAC protocols and the recent implementation of SMAC in WSN applications.

3. Medium Access Control (MAC) Protocols for WSN

The media access control (MAC) layer is the second layer in WSNs that coordinates channel access to the shared medium of WSNs [136]. The rationale for designing MAC protocols is to ensure channel fairness, avoid packet collisions, and, most importantly, maximize energy efficiency in the MAC layer [137]. Despite the traditional MAC protocol's attempt to minimize packet collision, there are still sources of energy waste in the MAC layer. Packet collision, overhearing, idle listening, and control overheads caused by ready to send (RTS), clear to send (CTS), and acknowledgement (ACK) control frames are all sources of energy wastage. The size of headers and trailers can sometimes contribute to energy waste [138]. MAC protocols are intended to ensure the quantitative measures of quality of service such as channel fairness, network throughput, delay/latency, scalability, and robustness [139] in WSN applications. Although primitive MAC protocols such as ALOHA and CSMA do an excellent job of avoiding packet collisions, the best way to reduce energy waste is to use low duty cycling. The radio transceiver unit of a sensor node is switched to sleep when idle. As a result, our review paper focuses on developments in low duty cycle (LDC) MAC, with particular emphasis on the synchronous low duty cycle (i.e., sensor MAC (SMAC)).

3.1. Low Duty Cycle (LDC) MAC Protocols for WSN. Duty cycling is used in digital and logic systems, electric motors, air compressors, and lighting systems in our homes and offices to save energy by switching them on and off. When necessary, these devices are switched on and turned off as soon as they are no longer required or the task for which they were switched is finished. The on and off (duty cycling) principle is also used in WSNs, specifically MAC protocols. Duty cycling in WSNs reduces the energy dissipation, specifically idle listening and packet overhearing [121]. In WSNs, energy dissipation is a critical design issue. According to research, the amount of energy consumed by SNs while listening to a channel without communicating and receiving unnecessary packets is nearly the same as the amount of energy consumed in packet transmission and reception in the radio transceiver unit [31]. As a result, there is a need to address the issue of energy consumption; duty cycling has proven to be one of the most efficient solutions [40, 41, 121, 140, 141].

Duty cycle MAC protocols regulate the radio of SNs, alternating between active and sleep modes [119]. SNs in active mode can sense, monitor, transmit, and receive data packets, and they automatically switch to sleep mode when there is no event to sense and transmit [142]. The sleep/wakeup period is the total cycle of the network's SN's periodic listen and sleep off the SNs in the network [121]. Because the sleep mode consumes almost no energy, the energy consumption during idle listening is reduced. Although duty cycling aims to put SNs to sleep for extended periods to save energy, there is a tradeoff in end-to-end delay and high energy consumption due to node synchronization [143]. When all SNs are in active mode, they communicate with their next-hop neighbours.

On the other hand, active nodes targeting sleep modes may have to wait until the sleep cycle is completed before receiving the transmitted data packets. Long waiting periods cause delay, affecting latency [141]. Furthermore, some duty cycle schemes necessitate node synchronization by broadcasting their schedules across the network whenever a schedule is created. Node synchronization consumes more energy because it takes more energy to create and broadcast schedules. Furthermore, a long wakeup period followed by a short sleep cycle increases energy consumption because SNs require a lot of energy to stay active for a long time [141].

LDC-MAC protocols may be classified based on the following criteria: (1) The synchronization mechanism, (2) The length of the preamble, (3) The receiver or transmitter initiation mechanism, (4) The number of channels required, (5) Random or on-demand wakeup, and (6) Clustering [40, 121]. In this paper, LDC-MAC protocols are classified as synchronous, asynchronous, and semisynchronous/hybrid schemes adapted from Ahmad et al. [121]. Asynchronous schemes do not require synchronization because nodes sleep and wakeup independently of the other nodes in the network [99]. Asynchronous schemes include protocols that use receiver-initiated, transmitter-initiated, preamble-sampling, on-demand wakeup, and random approaches [144, 145]. In the receiver-initiated approach, SNs will notify their neighbours that they are ready to receive data packets. Such notification can be in the form of a preamble, control packets, and acknowledgements. The SNs will continue to use these notification packets until they reach the active period of the destined SN in the transmitter-initiated approach.

In the preamble-sampling approach, the burden of energy consumption by the receiver is shifted to the sender. Nodes sleep asynchronously and wakeup occasionally to check preamble transmission and then wait for incoming data frames [40]. On the other hand, sensor nodes in the sleep state are switched to the listen/wakeup state immediately when needed in the on-demand wakeup approach. In contrast, nodes in the random approach switch between sleep and wakeup at irregular intervals. Examples of asynchronous schemes include Wise MAC [146], Berkeley MAC (B-MAC) [94], and Short Preamble MAC (X-MAC) [95], and Asynchronous IEEE 802.15.4 [144] protocols.

Protocols in synchronous schemes create schedules to put SNs to sleep and wake them up simultaneously. Rendezvous and skewed/staggered synchronous schemes are two synchronous schemes that are widely used [40, 145]. In the synchronous rendezvous scheme, all sensor nodes turn their radio transceivers on and off simultaneously using a guard time. In contrast, nodes wakeup in the skewed/staggered synchronous scheme at different times. However, a synchronization mechanism that controls how nodes can simultaneously turn their radios on and off is required in both rendezvous and skewed/staggered schemes. Examples of synchronous schemes are Power-Aware Clustered TDMA (PACT) [147], Low-Energy Adaptive Clustering Hierarchy (LEACH) [148], Self-Organizing Slot Allocation, Timeout-MAC (T-MAC) [149], Traffic-Adaptive Medium Access [150], Dynamic MAC (DMAC) [151], Synchronous IEEE 802.15.4 MAC [144], Sensor MAC (SMAC) [61], and many more. In their operation, the semisynchronous/hybrid scheme duty cycle scheme combines the advantages of synchronous and asynchronous schemes, such as easy synchronization of neighbour nodes in the clustering/synchronous scheme [40]. Random, spontaneous clustering, topology control, sentinel, comparative schedule, and elected cluster-head are all examples of the semisynchronous scheme [40, 145].

In spontaneous clustering, nodes organize themselves into clusters without an elected head. In contrast, in an elected cluster-head semisynchronous scheme, nodes are elected as cluster heads to coordinate the activities of cluster formation and traffic aggregation. On the other hand, the sensor MAC (SMAC) protocol is usually classified as a synchronous scheme due to its fixed schedules and node time synchronization. However, Carrano et al. [40] classified it as a semisynchronous scheme due to virtual cluster formation after nodes broadcast their schedules for other nodes to follow. Figure 5 depicts the various low duty cycle MAC protocols classification discussed in this paper. The three major categories of LDC-MAC protocol are described in the following sections. Our discussion highlights key developments in each category and compares the three groups (i.e. synchronous, asynchronous, and semisynchronous).

3.1.1. Synchronous Low Duty Cycle (SLDC) Protocols. In SLDC schemes, MAC protocols typically use sleep/wakeup schedules (i.e. sleep and wakeup time of sensor nodes) that necessitate node synchronization. Sleep/wakeup schedules are then broadcasted in the network for nodes to follow, determining when a node goes to sleep to save energy and the time nodes can wakeup to communicate. Some MAC protocols in this scheme use adaptive duty cycling, where the duty cycle is altered based on the traffic load [67, 149, 152, 153]. Thus, the sleep/wakeup periods alternate depending on the traffic load: long active periods for heavy traffic loads and vice versa.

The periodic sleep/wake cycle consists of a sleep period represented by Tsleep and the active period denoted by Tactive in each cycle of Twakeup-period as shown in Figure 6 [154]. Figure 6 depicts how SLDC works, with synchronization achieved through frequent beacon frame transmissions. When a node enters the active period, it broadcasts its beacon frames to neighbouring nodes to share its current schedule and status information [121]. Hence, all nodes can learn about the schedules of their neighbours and use this information for data communication.

The carrier sensing of the active period is when the channel is sensed for any incoming data packet or to see if the channel is free before sending the data frame to the destination node. SNs are synchronized via a long preamble reception of beacon frames from neighbouring nodes to discover their schedules and frequency channels [154]. The sleep/wake schedule is frequently used in continuous monitoring because of its periodic traffic pattern [155]. Synchronous schemes save energy, but their synchronization mechanism necessitates additional control packets [145]. Sensor MAC (SMAC), proposed by [61], was the first and most widely used synchronous duty cycle protocol developed to reduce idle listening, while T-MAC [149], DSMAC [156], and ADV-MAC [66] SMAC's limitations (such as fixed duty cycle, long sleep period, and energy wastage) were addressed by SLDC protocols. These protocols lay the foundations for more recent synchronous schemes. Most researchers investigate SMAC and offer solutions to its limitations, focussing on increasing network throughput, latency, and network lifetime. A comparison of critical SLDC MAC protocols is shownin Table 2.

3.1.2. Asynchronous Low Duty Cycle (ALDC) MAC Protocols. Unlike in the synchronous scheme, where SNs sleep and wakeup simultaneously, SNs in the asynchronous scheme have different sleep and wakeup periods and do not require node synchronization. Asynchronous protocols use channel/preamble sampling and low power listening (LPL) [163]. Most of the time, the SNs sleep, but they wakeup to sense the channel for a preamble or send preambles to notify target receivers of incoming data packets within a time interval.

Target receivers stay awake to receive all the data packets after detecting a preamble, while nontargeted receivers sleep. Each of the frames transmitted begins with a long preamble denoted by Tpreamble that lasts longer than the channel interval denoted by Tinterval shown in Figure 7 at the start of transmission in asynchronous schemes [154]. The periodic channel sampling uses this to detect the preamble of each transmission before the transmission of the actual data. In contrast to synchronous schemes, asynchronous schemes have lower packet overhead because there is no fixed sleep/wakeup for synchronization and virtual clustering. Although asynchronous schemes outperform synchronous schemes in a multihop network with low data rates and heavy traffic loads, low energy consumption, frequent channel sampling, long preambles for transmission and reception, and high overhearing result in increased energy dissipation [154]. Some popular asynchronous low duty cycle MAC protocols

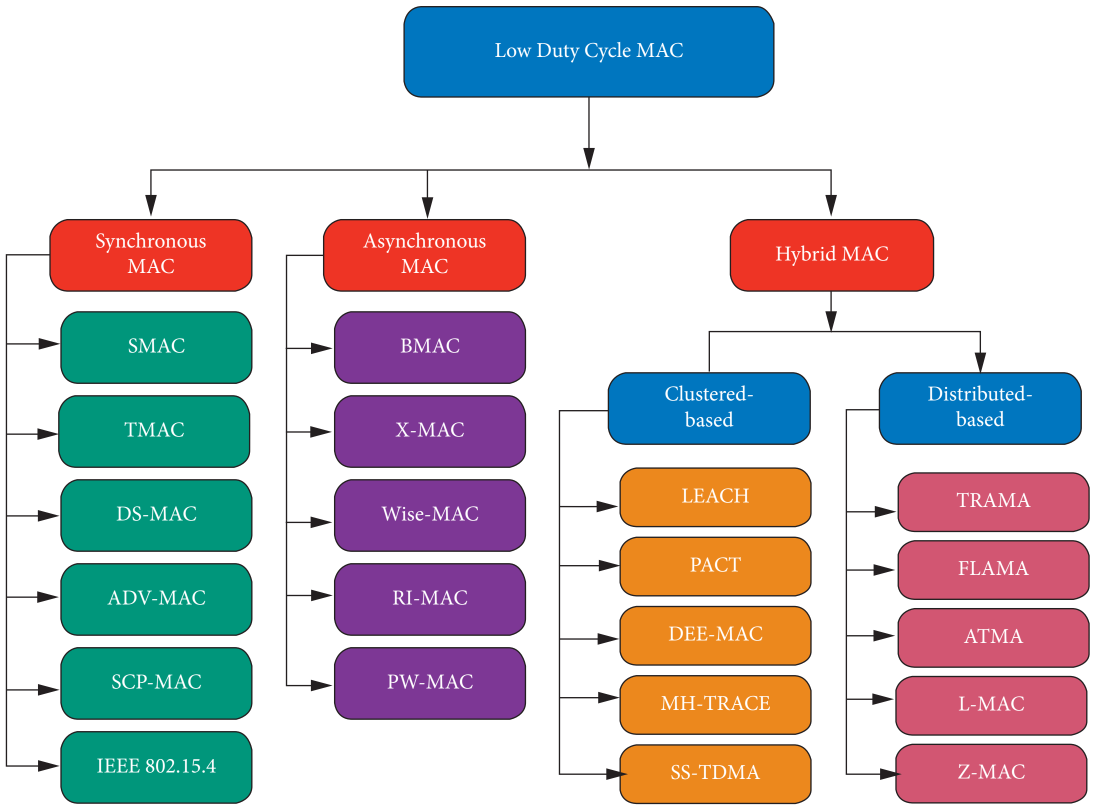

Figure 5: Low duty cycle MAC protocols for WSN.

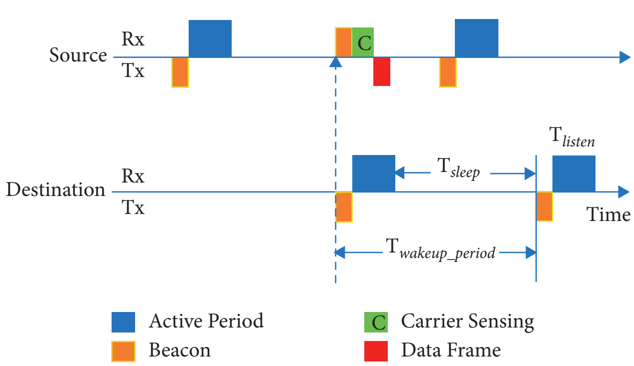

Figure 6: A synchronous periodic wakeup scheme adapted from the study by Ahmad et al. [121].

include Berkeley MAC (B-MAC) [94] and Wise MAC [146], and short preamble MAC (X-MAC) [95]. Table 3 illustrates a comparative study of some key ALDC MAC protocols.

3.1.3. Semisynchronous Low Duty Cycle (SSLDC) MAC Protocols. SSLDC MAC protocols combine the features of synchronous and asynchronous to reduce energy dissipation in WSNs. Clusters of SNs are frequently formed, and nodes in each cluster are synchronized to wakeup or sleep simultaneously, but clusters communicate asynchronously [145]. Hybrid schemes are another name for semi-synchronous schemes. Hybrid protocols include Low-Energy Adaptive Clustering Hierarchy (LEACH) [148], Zebra MAC (Z-MAC) [174], and Flow-Aware Medium Access (FLAMA) [175]. Table 4 depicts a comparative study of SSLDC MAC protocols.

4. Sensor MAC (SMAC) Protocol

SMAC [61] is a well-known synchronous low duty cycle protocol that improves the 802.11 protocol. The SMAC protocol seeks to reduce the sources of energy dissipation in the MAC layer by addressing issues such as idle listening, packet overhearing, packet control overhead, and packet collision. Through the SMAC's periodic listen and sleep mechanism, the SN's radio is switched between active and sleep modes based on the SN's schedule for sleep and wakeup periods reducing idle listening. SMAC uses the 802.11 protocol's Request-to-Send (RTS), clear-to-send (CTS), and carrier sensing (CS) mechanisms to avoid collisions caused by hidden and exposed terminals that cause packet collisions in the MAC layer. The SNs are put to sleep to avoid packet overhearing (i.e. preventing SN from receiving unintended/uninterested packets). As a result, neighbour nodes that may interfere with the receiver and the sender fall asleep immediately after hearing or sensing the RTS or CTS. Furthermore, the SMAC protocol's message passing mechanism reduces packet control overheads by breaking the long messages into small fragments and sending them in a burst. Moreover, the RTS/CTS/DATA/ACK mechanism ensures that all data fragments are successfully transmitted from the sender to the receiver.

Since its inception, SMAC research has focused on investigating and improving SMAC's shortcomings for

Table 2: Comparative study of SLDC MAC protocols.

Reference	Problem identified	Proposed solution	Limitation
Lin et al. [156]	Sleep delays, fixed duty cycle	SMAC with dynamic duty cycle (DSMAC)	Increased overhead
[157]	Delay	SMAC with adaptive listening	Long end-to-end delay
[158]	Data forwarding interruption problem, latency, and fixed duty cycle of LDC-MAC protocols	Energy-efficient and low latency MAC (DMAC) protocols are proposed.	Increased overhead alongside traffic load and network topology limited to tree-based topology
[159]	Latency in multihop forwarding, end-to-end delivery latency, poor traffic contention control	Routing enhanced MAC (R-MAC) protocol	Collisions due to two hidden terminals
Ray et al. [66]	Idle listening, energy wastage in T-MAC	Advertisement MAC (ADV-MAC)	Increased overheads
[160]	High energy dissipation of sensor nodes as a result of random movements, as well as the use of RSSI in predicting mobility in mobility-aware SMAC (MS-MAC)	Energy-efficient mobility-aware SMAC (EMS-MAC) protocol	Limited mobility zones, high mobility failures
[161]	Energy dissipation in idle listening	Improved T-MAC with power saver mode	Increased overhead
[162]	Energy dissipation, fixed duty cycle, queuing delay	Energy-efficient and QoS-aware (EEQ)	Homogeneous scenarios, symmetric radio channel

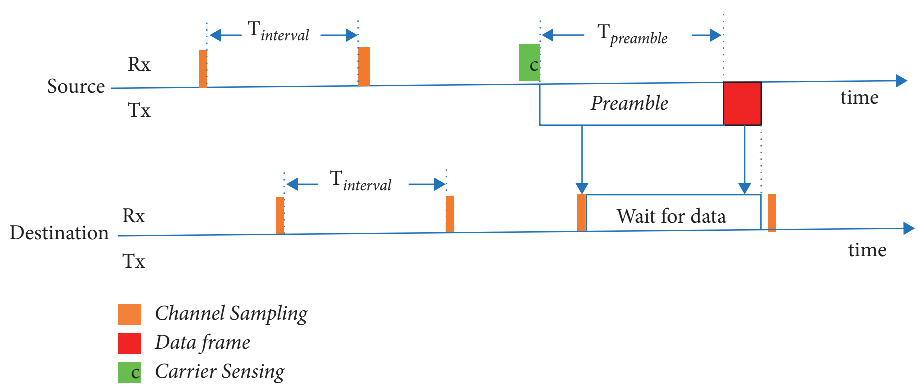

Figure 7: The operation of asynchronous duty cycle [154].

WSN applications. T-MAC protocol, for example, was created to compensate for SMAC's fixed duty cycle [149]. Some studies did propose improvements in latency, adaptive duty cycle, and energy efficiency in SMAC by Lin et al. [156]; Ye et al. [157]; Lu et al. [158]; and Suh and Ko [177]. T-MAC could be further enhanced by adjusting RTS, CTS, DATA, and ACK's transmission power levels [178–180] proposed and analyzed the significance of the schedule unifying algorithm for eliminating border node problems in SMAC. Although SMAC propositions are more energy-efficient, adaptable to traffic load variations, and improve network performance, traditional SMAC is still being investigated to suit current WSN application design and provide insights and innovative ideas for researchers and developers. As a result, researchers use the following criteria to address the issue of fixed duty cycle and contention window for traffic adaptation in SMAC: (1) A mechanism for reversal, (2) A duty cycle mechanism; and (3) A power control mechanism for the transmission [181]. Because traffic load variations in WSN are difficult to predict, proposed SMAC backoff mechanisms dynamically adjust the contention window of SMAC to accommodate changes in network traffic load [64, 68, 181]. On the other hand, adaptive duty cycle mechanisms dynamically adjust the duty cycle of SMAC to account for variations in traffic load. To conserve energy, SMAC's sleep period is reduced during high traffic periods and increased during low traffic periods [182].

The duty cycle of SMAC can be tuned based on traffic loads [67], node strength, and the use of fuzzy logic to determine network traffic load uncertainties [152], traffic pattern, unnecessary idle listening [63], traffic loads prediction models such as the auto-regressive and moving average (ARMA) [183], duty cycle factor or threshold [184], and queue management, and feedback control systems [185]. Additionally, SMAC's transmission power control mechanism compensates for the shortcoming of fixed transmission power's high energy consumption. Nodes' transmission power is dynamically adjusted to minimize collisions, establish more reliable links, maximize medium/channel reuse, and maintain a low energy cost during communication [186]. Ideally, nodes' ideal transmission powers are identified, computed, assessed, and stored before being

Table 3: Comparative study of ALDC MAC protocols.

Reference	Problem solved	Proposed solution	Limitations
[94]	Idle listening, collision, channel utilization	Berkeley MAC (B-MAC) protocol	Large overheads caused by preambles
[146]	Idle listening, collision, long preamble, control overhead	Wireless MAC (wise MAC)	High latency
[95]	Low-power listening	Short preamble MAC (X-MAC) protocol	Inability to handle immediate traffic fluctuations
[164]	Energy consumption, overhearing and idle listening of sender-based scheduling approach for asynchronous MAC protocols.	O-MAC is based on a pseudorandom staggered for optimal energy efficiency	Collisions, no defined retransmission mechanism for collisions
[96]	Latency, long preamble	Receiver-initiated MAC (RI-MAC) protocol	Increased sender duty cycle and end-to-end latency.
[165]	A tradeoff between energy dissipation and latency	Express MAC (EX-MAC) protocol	Frequent collisions as well as extra reservation traffic
[166]	Hardware and operating system delays and clock drifts, energy consumption	Predictive-wakeup MAC (PW-MAC)—on-demand prediction error correction, efficient prediction-based retransmission mechanisms.	Increased overhead as a result of beacons and idle listening
[167]	End-to-end delay in multihop WSN	Cooperative low-power MAC (CL-MAC) protocol	Inadequate analysis of the backoff algorithm's effects on throughput, delay, and energy consumption
[168]	Collision, delivery latency, and control overhead	The sender centric MAC (SC-MAC) protocol avoids channel collision in burst traffic with reduced control overhead and optimizes packet delivery latency.	Overheads due to irregular periods and high energy dissipation for data transmission over channel reservation
[169]	Energy dissipation, latency, overheads	Low-latency asynchronous MAC (LA-MAC) protocol	Collisions in congested WSN
[172]	Long end-to-end delay of asynchronous LDC-MAC protocols	Virtual tunnel (VT) MAC protocol	Possible collisions due to on-demand synchronization
[171]	Energy dissipation	Energy-efficient asynchronous QoS (AQSen-MAC)	Performance of AQSen-MAC compared with only receiver-initiated QoS protocols and no other ALDC MAC protocols

Table 4: Comparison of studies on semisynchronous low duty cycle MAC protocols.

Reference	Problem solved	Proposed solution	Limitations
[148]	Static clustering, energy dissipation of fixed positions of cluster heads	Low-energy adaptive clustering hierarchy (LEACH)	Fixed clustering structure, designed for homogeneous sensor network scenarios
[172]	Number of transceiver switches, the fixed sleep interval	Lightweight MAC (L-MAC) protocol	Fixed frame length
[150]	Collision, idle listening, channel utilization	Traffic-adaptive medium access (TRAMA) protocol	Increased idle listening and overhearing
[173]	Idle listening, intracluster and intercluster data collisions	Multihop time reservation using adaptive control for energy efficiency (MH-TRACE)	Not adaptable to topological changes
[174]	Latency, channel utilization	Zebra MAC (Z-MAC) protocol	Adds additional overhead to detect abandoned slots, hidden terminal problem
[175]	Idle listening, data collision, delay	Flow-aware medium access (FLAMA) protocol	Complex and inflexible
[176]	The hidden terminal problem of Z-MAC	An improved Z-MAC protocol introduces tiny RTS/CTS packets to address the hidden terminal problem of Z-MAC and an enhanced DRAND algorithm for neighbour discovery	A tradeoff between overheads and collisions

dynamically alternated before minimizing energy consumption. Power control in SMAC (PSMAC) [187, 188], power controlled sensor MAC (PC-MAC) [189] and dynamic power control MAC (DPCMAC) are some of the fundamental transmission power control mechanisms for SMAC [190].

In this section, we present a review of the limitations of SMAC and suggested improvements to these limitations. This section also covers the simulation tools and performance metrics used in their design and implementation.

4.1. Limitations and Improvements in SMAC. This section investigates the current state of the art on SMAC from 2009 to date to determine the advances, challenges, and future directions of SMAC that are important to WSN researchers and developers. From 2009 to the present, we have studied and reviewed SMAC publications based on the following criteria: (1) High energy consumption of border nodes' adoption to multiple schedules, (2) Fixed duty cycle, (3) Increased end-to-end delay or latency. (4) Fixed contention window or poor backoff algorithm, (5) Unnecessary idle listening, and (6) Significant control overheads. Figure 8 depicts the literature on improvements and limitations of the original SMAC protocols and the percentage of publications addressing the associated challenges.

In the following sections, we discussed these limitations and the suggested improvements provided thus far by various researchers in the field.

4.1.1. High Energy Consumption of Border Node's Adoption of Multiple Schedules in SMAC. Node synchronization in SMAC's periodic listen and sleep generates virtual clusters where nodes adhere to a schedule. On the other hand, nodes straddling two or more clusters tend to use multiple schedules from the clusters for intercluster communication (see Figure 9). Border nodes or intermediary nodes exist between different clusters. These border nodes deplete their energy more quickly because they must stay awake for extended periods due to the network's multiple schedules. SMAC has high energy consumption and a short network lifetime due to border nodes using multiple schedules. Many solutions have been proposed to reduce or eliminate the number of border nodes in the network to ensure maximum network lifetime and mitigate high energy consumption (see Table 5).

Reference [191] eliminates border nodes and replaces them with a sink node that acts as the synchronizer to create and broadcast node sleep schedules, whereas [62, 103] propose a unified scheduling algorithm. The sensor nodes are forced to follow a single sleep and wakeup schedule to avoid the multiple schedule adoption by border nodes, thereby reducing high energy consumption. However, [192] employed the selective intermediate node (SIN) algorithm to minimize border node energy consumption. Nodes in the SIN algorithm send unicast messages to a synchronizer announcing its schedule and requesting permission to follow its schedule. When a unicast message is received, the synchronizer sends an acknowledgement to a selected node. The additional schedule to the one already assigned to them can only be followed by nodes that have received an

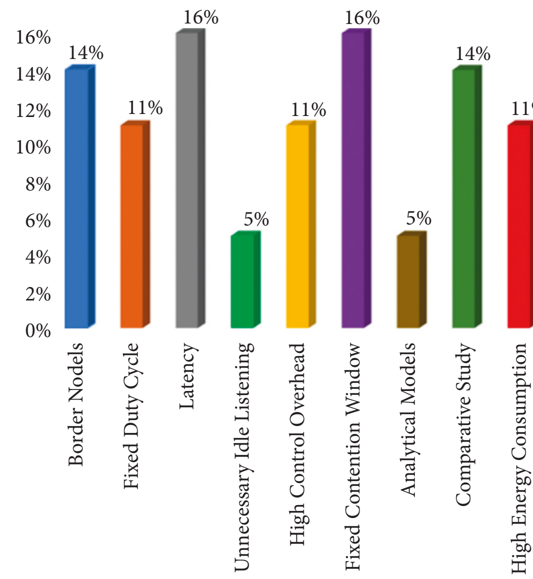

FIGURE 8: Distribution of publications on improved SMAC limitations.

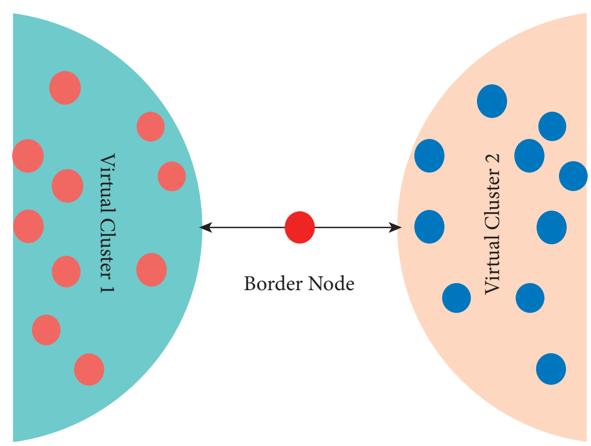

FIGURE 9: Border nodes' adoption to multiple schedules in SMAC.

acknowledgement. Thus, a border node requests a different schedule only if the synchronizer responds with an ACK. Hence, SIN reduces the multiple schedules of border nodes. Some proposed protocols save energy at the expense of increased control overhead to reduce the energy consumption of border nodes [103, 192]. Control overhead may increase as the enhanced protocols introduce additional fields and modifications to the original SMAC SYNC packet.

4.1.2. Fixed Duty Cycle. The periodic listen and sleep mechanism in SMAC saves energy by utilizing a fixed duty cycle that determines fixed sleep and listening periods. SMAC's fixed duty cycle is volatile because a long listen followed by a short sleep period for low traffic may result in extended idle listening. A long sleep period followed by a short listen period, on the other hand, may result in increased latency. Furthermore, a fixed duty cycle is unsuitable for a network with varying traffic loads because the duty cycle

Table 5: Improved protocols for high energy consumption in SMAC protocol.

Reference	Problem	Proposed solution/Purpose	Description	Limitations
	High energy consumption of border nodes in SMAC	Schedule unifying algorithm (SUA)	SUA tracks the multiple schedules followed by the border nodes and immediately triggers a procedure to unify the schedules.	# High control overhead # Network throughput not measured.
[191]	High energy consumption of border nodes	Low overhead WSN MAC (LO-MAC)	Introduced a unified schedule that lessens the synchronization time of the original SMAC by avoiding sending sync packets.	# No intercluster communication # Not adaptable to an extensive network # Higher average delay as sending interval increases # Has shorter sleep time
[192]	High energy consumption of border nodes	An enhanced SMAC is proposed using selective intermediate nodes (SIN)	# SIN is utilized when border nodes send a unicast request to follow a schedule that is already following another schedule. # An ACK is sent to nodes allowed to adapt to the schedule to reduce the number of schedules adopted by a border node.	# Algorithm does not expatiate. # High control overhead
[193]	Forced wakeup problem in adaptive SMAC	CL-MAC protocol	The CL-MAC protocol utilizes routing layer information to determine nodes that need to be awake to communicate. Hence, nodes in sleep modes are excluded from the routing paths for data transmission.	# It does not ensure fairness in terms of the traffic loads # Simulation tool not mentioned.
[189]	High energy consumption	Power controlled sensor MAC (PC-MAC)	# Modified the SMAC schedule table to include each node's minimum power levels. # Uniform, exponential, and Gaussian distributions were used for the experiment.	# The protocol is limited to reducing only the transmission power and energy consumption
[62]	High energy consumption of border nodes	A new unified scheduling algorithm is introduced to improve the lifetime of border nodes.	Constructs border nodes and broadcasts uni-scheduling packets from the border nodes to unify all schedules into a single schedule	# High control overhead # Throughput not measured
[101]	High energy consumption of border nodes	Improved SMAC algorithm by merging virtual clusters	Virtual clustering in the original SMAC is modified to merge clusters to follow one cycle, thereby reducing the number of border nodes' multiple schedules	Cross-layer optimizations
108	# Inefficient use of energy # Transmission of redundant data	Energy-efficient sensor MAC (ES-MAC)	A dynamic duty cycle is utilized # Modified SMAC and T-MAC algorithms. # Selective data transmission is used to minimize the number of transmitted packets sleep interval improved by applying data cycle (DDC)	# Multihop scenarios # Back-off mechanism
[194]	High energy consumption	ASS-MAC protocol dynamically alters the nodes' sleeping time based on the last observed traffic.	The protocol "provides the schedule of the next period based on network behaviour during previous periods to adapt to network traffic"	# Network throughput

is not adaptable to load variations. The fixed duty cycle can be solved by employing dynamic and adaptive scheduling techniques, as illustrated in Table 6, in which node sleep and listen periods are dynamically altered to accommodate the network's various traffic loads and routing algorithms. Unlike protocols that dynamically adjust the fixed duty cycle based on traffic load [67, 153], node actual traffic strength [152], Jagriti [63] proposes an analytical model that alternates the sleep mode based on unnecessary idle listening. Zhang et al. [152] use a fuzzy logic system to determine traffic uncertainties and dynamically adjust the fixed duty cycle of the original SMAC based on the traffic pattern.

4.1.3. Increased End-to-End Delay/Latency and Packet Loss. Increased latency or end-to-end is the tradeoff for SMAC's low energy consumption due to the fixed duty cycle, particularly long sleep periods of SMAC. As a result, nodes awake

Table 6: Enhanced protocols/algorithms for fixed duty cycle limitation of SMAC protocol.

Reference	Problem	Proposed solution/Purpose	Description	Limitations
[152]	Fixed duty cycle control overhead	AD-MAC protocol	An adaptive duty cycle is proposed where the duty cycle, particularly the sleep schedule, is altered to accommodate different traffic patterns. Wake-up time can be extended for incomplete data transmissions.	# Packet delivery ratio and throughput not considered.
[153]	Fixed duty cycle	L-MAC protocol	The use of a fuzzy logic system to determine node traffic uncertainties. Dynamically adjust the duty cycle of SMAC to adapt to changes in the environment of greenhouse environmental monitoring	# Performance evaluation is limited to energy consumption. # Algorithm for the protocol not clearly given
[110]	Fixed duty cycle and unnecessary idle listening.	Designed a novel analytical model to mitigate unnecessary idle listening caused by a fixed duty cycle.	A novel analytical model is designed to conserve energy and reduce unnecessary idle listening by creating a dynamic sleep period depending on the traffic conditions.	# They excluded how the model dynamically puts nodes to sleep to conserve energy. # The reason for exempting the sensing energy for the computation of total energy was not given.
[67]	Fixed duty cycle and idle listening	Variable traffic-adaptive duty cycle sensor MAC (VTA-SMAC)	Virtual clustering, adaptive duty cycle, and dynamic sleep algorithms are utilized to solve high energy consumption of border nodes, traffic load variation and low data traffic issues of SMAC, respectively	# A comparative paper of VTA-SMAC and other asynchronous low duty cycle MAC protocols. # Implementation of VTA-SMAC in NS-3 # Repetitive calculation of duty cycle.

and ready-to-send data packets to their neighbour nodes during their sleep periods must wait until they wakeup and are ready to receive. Sleep delay refers to the end-to-end delay caused by the sleep schedule. SMAC's sleep delay causes packet loss because packets are dropped when they reach next-hop neighbours in sleep modes. The increased delay/latency is caused by SMAC's fixed duty cycle, so the duty cycle should be adjusted to avoid end-to-end delay. To minimize delay in transmitting high-priority data, [195] propose ADV-SMAC, introducing two message queues: high priority and low priority. The duty cycle of SMAC is adjusted based on the number of messages in a node's queue [196]. As a result, the duty cycle increases when the number of queued messages exceeds a certain threshold. In contrast, a fast-binary exponential backoff algorithm is proposed to reduce latency [109]. Table 7 depicts ongoing research on mitigating high end-to-end delay/latency and packet loss incurred at the expense of mitigating idle listening in SMAC protocol.

4.1.4. High Control Overhead. High control overhead occurs as a result of the exchange of schedule information for node synchronization and neighbour discovery, as well as the exchange of control packets such as ready to send (RTS), clear to send (CTS), and an acknowledgement (ACK) among sensor nodes to avoid packet collision and overhearing in the SMAC protocol. These control packets have high overheads and require more energy to exchange, thereby increasing energy consumption. Investigations into the SMAC protocols have shown high control overhead cost incurred while mitigating idle listening. Hence, optimal solutions have been proposed to improve on this shortcoming in SMAC (see Table 8). For instance, the SYNC, RTS, CTS, and ACK from the original SMAC can be combined, for example, SYNC plus RTS at the start of the node's cycle to avoid high control overheads, and ACK plus RTS for bidirectional transmissions [138]. To save energy, the components of the SMAC data frame headers and trailers can also be minimized [152].

4.1.5. Unnecessary Idle Listening. SMAC's primary goal is to reduce idle listening and packet collision. On the other hand, the fixed duty cycle of SMAC's periodic listen and sleep mechanism incurs some costs in idle listening, particularly in long listening periods for low traffic loads. Nodes with no data to send or receive are forced to remain idle until their listen time expires. According to Yang and Zhang [193]; nodes are forced to wakeup for idle listening if they are part of a communication routing path. They proposed CL-MAC, which applies route information to wakeup nodes with actual data and forms part of a communication routing path. CL-MAC is implemented in RTS and CTS control frames by including the final destination address and the following communication address. Furthermore, the combination of MAC and PHY layer information has been shown to reduce unnecessary idle listening in situations where nodes are designed to proactively inform their neighbours of their data transmission plans [65]. Table 9 elaborates on propositions for mitigating unnecessary idle listening in SMAC protocol.

Table 7: Enhanced protocols/algorithms for increased end-to-end delay/latency and packet loss of SMAC protocol.

Reference	Problem	Proposed solution/ Purpose	Description	Limitations
[196]	Latency and redundant packet transmission	Express energy-efficient media access control (EX-MAC)	EX-MAC introduces a mechanism that dynamically adjusts the duty cycle based on the traffic load or message queue.	The minimization of redundant packet transmission is not clearly explained and justified. High control packet overhead.
[197]	Delay and packet loss for high-priority applications	Advanced SMAC (ADV-SMAC) protocol	# The protocol uses different queues for high priority and low priority traffic. # It uses a contention-based approach for low priority traffic, while a TDMA approach is used for high-priority traffic. # Channel sensing is excluded in ADV-MAC for high-priority packets to aid in faster transmission and reduce end-to-end delay.	# Collisions may occur in sending high-priority packets in ADV-SMAC as channel sensing is excluded in the subphases.
[112]	Delay	Designed an analytical model of SMAC Analyzed the delay SMAC	An analytical model of a multihop wireless sensor network incorporating the original SMAC protocol that constitutes a network controller based on network delay for multihop and single-hop scenarios.	# The effects of network scheduling algorithm on network stability. # Analytical model on throughput and energy consumption
[198]	Delay in sending and processing high-priority data	Addition of priority bits to the beacon frame of SMAC for WVSN	# The priority bit introduced in SMAC indicates criticality and the need to process that data first in the coordinator. # The priority bit is either 0 or 1. A data sent with a priority bit set to 0 indicates that the data is critical and must be processed first and vice versa.	# The adaptability of the proposed algorithm in mesh or ring topologies.
[78]	Latency	Division-multiple access-media access control (MDA-SMAC)	# MDA-SMAC applies fast-binary exponential backoff algorithm to reduce data latency. # To reduce the collision probability of data, schedules are split into multiple microduties. # Adopts adaptive duty cycle and backoff algorithm.	# Heterogenous scenarios

Table 8: Enhanced protocols/algorithms for high control overheads in SMAC protocol.

Reference	Problem	Proposed solution/Purpose	Description	Limitations
[152]	High control overhead	AD-MAC	# An adaptive duty cycle is proposed where the duty cycle, particularly the sleep schedule, is altered to accommodate different traffic patterns. # Minimized SMAC data frame headers and trailers by. . ..	# Packet delivery ratio and throughput not considered.
[138]	High control overhead	Adaptive energy-efficient MAC (AEEMAC)	AEEMAC protocol combines the SYNC and RTS control packets into one and RTS and ACK packets to reduce the number of control packet exchanges in the original SMAC.	# Comparative paper of AEEMAC with other MAC protocols.
[199]	High control overhead	Comparative paper of SMAC (synchronous MAC protocol) and RI-MAC (asynchronous duty cycle MAC protocol).	Performance analysis of SMAC and RI-MAC based on contending flow and data gathering scenarios.	# Missing improved SMAC's high control overhead and energy consumption in a contending flow scenario.

Table 9: Proposed protocols/algorithms for mitigating unnecessary idle listening in SMAC protocol.

Reference	Problem	Proposed solution/Purpose	Description	Limitations
[193]	Unnecessary idle listening	CL-MAC protocol	The protocol utilizes routing layer information to determine nodes that need to be awake to communicate. Hence, nodes in sleep modes are excluded from the routing paths for data transmission.	# It does not ensure fairness in terms of the traffic loads # Simulation tool not stated.
[65]	# Unnecessary idle listening # Fatal bugs in the original implementation of SMAC in NS-2	# A mechanism known as announce to send (ATS) is proposed # The original implementation of SMAC was modified to fix fatal bugs	ATS solves unnecessary idle listening in SMAC by proactively informing its neighbour nodes of their transmission plan.	# Overhearing and packet collisions

Table 10: Enhanced protocols/algorithms for fixed contention window/poor backoff algorithm.

Reference	Problem	Proposed solution/ Purpose	Description	Limitations
[202]	Fixed contention window	An improved SMAC protocol is proposed.	Enhanced SMAC algorithm that adjusts the contention window according to the traffic load in coal mine WSN.	# Localization of mobile sensor nodes in the coal mine tunnels.
[200]	Poor backoff algorithm	Back-off depends on queue and retry (BDQR)	BDQR improve on the original backoff algorithm of SMAC by introducing a failure counter (Fcounter), q variable, and a disjunctive window threshold (CWm).	# The experimental results that reduced channel collision and improved node communication fairness were not clearly explained.
[64]	Fixed contention window/backoff algorithm	R-MAC in MAC layer	Combines adaptive contention window and forecasting data flow based on SMAC's nodes length of the queue.	# The algorithm for the protocol design is not given. # Unequal performance metrics for both star and mesh topological scenarios.
[201]	Fixed contention window	ACW-MAC protocol	Adjusts the SMAC contention window using self-adaptive and neighbour competition of the channel in conjunction with the MIMLD algorithm.	# Priority of packet transmission and topological changes.
[68]	Poor backoff algorithm	Adaptive back-off and duty cycle for SMAC (ABDC-SMAC)	The flow factor measures network traffic and dynamically changes the duty cycle for improved energy consumption and transmission delay.	The duty cycle is not varied.

4.1.6. Fixed Contention Window/Poor Backoff Algorithm. SMAC's backoff algorithm (i.e. an algorithm implemented to resolve collisions whereby the sensors wait for a random time before transmitting during collisions) consists of the physical layer's slot size and a random integer distributed between zero (0) and the fixed contention window (CW). The backoff time may be expressed as

$$B\text{time} = \text{random}^{*}\text{slotTime}, \quad (1)$$

where Btime represents the backoff time, random () is equal to [0, CW] and slot Time.

Researchers believe that because the CW of SMAC is fixed and constant, and the backoff time is computed from a random fixed CW that does not suit the dynamic nature of the channel state as well as the number of nodes in a real WSN environment, it should be improved [64]. Others argue that the SMAC backoff algorithm is simple, archaic, and unsuitable for dynamic channel states and improved node fairness [200]. Lu et al. [200] proposed a modification to the SMAC backoff algorithm that improves node fairness, collision avoidance, and network longevity, back-off depends on queue and retry (BDQR) algorithm. On the other hand, Qi et al. [64] dynamically modify the CW based on data reception success and failure. As a result, successful data receipt implies fewer accidents. As a result, the contention window is reduced to maximize network throughput and minimize latency while being increased for failed data reception to reduce packet collisions. Furthermore, [201] modified the SMAC contention window by using a self-adaptive contention window and channel neighbour competition. Although SMAC's improved contention window and backoff algorithms (see Table 10) have been demonstrated to improve energy efficiency, end-to-end throughput, and latency, packet transmission priority and network topological changes are not considered.

4.1.7. Analytical Modelling and Comparative Studies of SMAC. Analytical models are used by researchers to model protocols and undertake performance analysis. Some proposed protocols and performance analyses are accomplished

Table 11: Analytical modelling and comparative studies of SMAC.

Reference	Problem	Proposed solution/purpose	Description	Limitations
[105]	Energy consumption	A performance evaluation of SMAC in combination with OLSR, AODV, DSR and DSDV routing protocols to improve the energy efficiency of SMAC.	The routing protocols implemented in SMAC to determine the effect of routing protocol on the energy consumption of SMAC depending on the network topology and WSN application.	# Unknown reason for DSR failure in conjunction with SMAC implementation.
[203]	Energy efficiency and routing packet overhead	Comparative study of SMAC in AODV and AOMDV.	A comparative paper and evaluation of the impact of single path AODV and multipath AOMDV routing protocols on SMAC's energy efficiency and routing packet overhead.	# Throughput and latency were not considered.
[204]	Fixed duty cycle	A comparative study is conducted for SMAC and T-MAC.	The comparative paper was based on static and dynamic sleep schedules.	# No experiments or simulations to justify the comparative paper.
[205]	Energy consumption	SMAC and T-MAC performance analysis is based on a static and homogeneous network scenario.	The authors deduced that energy saving depends on the duty cycle value. The higher the duty cycle value, the more energy used and the less energy saving. Hence, a duty cycle of 10% was used in their simulation and analysis.	# Delay and throughput not considered.
[139]	Energy consumption	A comparative paper of SMAC and T-MAC.	A comparative paper was conducted on SMAC and T-MAC to ascertain the energy consumption of the protocols in a static network for two scenarios of 25 and 49 nodes.	# Factors influencing the high energy consumption of nodes in SMAC for the two scenarios were not given.
[102]	Energy consumption and throughput.	Performance analysis of SMAC and other protocols.	In conjunction with LEACH, LEACH-C, MTE and static clustering protocol, SMAC is analyzed and simulated.	# Simulation results on SMAC are not clearly explained.
[111]	Energy consumption, throughput and latency.	Analytical model for SMAC performance in a heterogeneous scenario with different medium access priorities.	# A two-dimensional discrete-time Markov chains (DTMC) are utilized in the model. # Performance parameters such as energy consumption, throughput, and average packet delay were modelled.	# Energy consumption of sensor nodes in application-specific environment excluded. # Infinite transmissions not considered.
[104]	Energy consumption, throughput, delay, and PDR.	SMAC performance evaluation in energy, throughput, delay and packet delivery ratio (PDR).	It dynamically adjusted the duty cycle according to the number of nodes and traffic load.	# Implementation of SMAC in NS-3 to compare results with that of NS-2. # No evaluation on traffic load variation.

using SMAC analytical models (see Table 11). Jagriti [63] proposed an analytical model that reduces energy consumption by stimulating the activities of a node in its active state. The activities were used to model the activities using the transmission energy, receiving energy, overall energy, switching energy, sleeping energy, sampling energy, and delay. Other literature designed models for multi-hop, single-hop, heterogeneous, homogeneous networks and performance metrics were derived from these models for performance evaluations [111–114]. SMAC protocols, on the other hand, are utilized as a performance benchmark for other energy-efficient MAC protocols through performance analysis and comparative studies.

4.2. Simulation Tools. Developing, testing, and experimenting with new and existing WSN algorithms, theories, and protocols in the early stages of design and evaluation in a real-world environment is costly, time-consuming, and challenging. During the early stages of network protocol design, developers and researchers test and evaluate the performance of protocols and algorithms to ensure their efficiency and accuracy before deploying or implementing in the real world to save money and ensure protocol accuracy. Some proposed algorithms and theories may also be impossible to implement in real-world scenarios. As a result, there is a need to simulate or emulate these theories and algorithms in controlled environments that are flexible, simple, and inexpensive. Tests, experiments, and evaluations can be repeated for accurate results before implementing or deploying them in a production environment. Network simulation is a popular WSN performance evaluation method among developers and researchers due to its effectiveness, feasibility, and low cost of evaluating and testing algorithms and protocols [206, 207].

Simulators, or simulation tools, simulate real-world components such as sensor nodes and network topologies [208]. They have built-in network protocols such as physical layer protocols, MAC layer protocols, transport layer protocols, routing protocols, and graphical user interfaces (GUIs). They also implement physical layer models like wireless transceivers, signal propagation and delay models, energy consumption models, and others [218]. Popular WSN simulators include Network Simulator version 2 (NS-2) [208–215], Network Simulator version 3 (NS-3) [211], Optimized Network Evaluation Tool (OPNET) [212–214], Objective Modular Network Testbed in C++ (OMNET++) [218, 215], and Matrix Laboratory (MATLAB) [218, 216, 217]. We investigated the simulators used by researchers to evaluate the performance of SMAC variants to identify the most commonly used simulators. It was discovered that the majority of SMAC's variants (66%) patronized NS-2 (see Figure 10) because it contains SMAC implementation and is thus easy to modify to suit proposed SMAC variants. In contrast, new models, frameworks, or implementations are created to depict proposed algorithms for those lacking SMAC modules such as NS-3, MATLAB, OMNET++, OPNET, and many more.

NS-2 is widely used because of the ease with which traditional SMAC can be modified; however, it is outdated and lacks updated features that support recent WSN enhancements. Furthermore, Kuo and Liu [65] discovered bugs in the NS-2 SMAC implementation module, such as the incorrect implementation of the backoff timer, incorrect time to initiate adaptive listening (AL), extended duration time for packet retransmissions, incorrect calculation of the number of fragments in SMAC's message passing, and many others. These flaws were never discovered in previous SMAC simulations. As a result of the author's assertion that the bugs mentioned above had a detrimental effect on SMAC's energy consumption. The bugs were fixed following the literature, and the simulation results improved energy consumption compared to the original SMAC implementation. Regardless of bugs in SMAC in NS2 implementation identified by Kuo and Liu [218]; no literature has either supported or refuted it. Other WSN simulators that support improved features and abstractions of recently improved WSN MAC protocols should be used by researchers.

4.3. Performance Metrics of SMAC. Performance metrics are typically used to quantify the quality of service provided by a computing system [36]. The most commonly used performance metrics in WSN are delay, throughput/packet delivery ratio, and energy consumption [219].

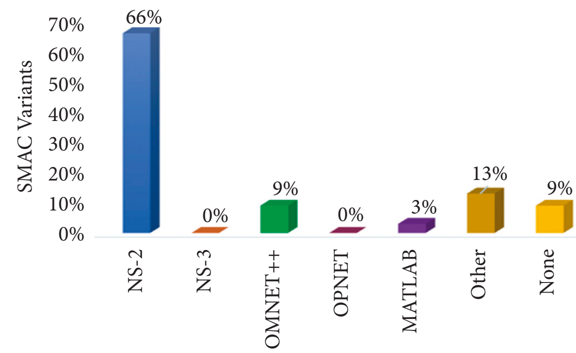

FIGURE 10: Distribution of WSN simulators used in SMAC variants.

4.3.1. Delay. The time it takes for a packet to travel from one node to another or from the source node to the destination node is also known as an end-to-end delay. End-to-end delay is typically measured in seconds or milliseconds (ms).

4.3.2. Packet Delivery Ratio (PDR). The ratio of the total number of packets received at the destination to the number of packets sent by the source node. This may be expressed as PDR = T_r/T_s where T_r = total number of received packets by the destined node and Ts = total number of sent packets by the source node. PDR is usually represented in percentages (%), i.e. PDR = $(T_r/T_s) * 100\%$.

4.3.3. Energy Consumption. Energy consumption is the quantitative measure of the sum of all energy dissipated by the various activities of the sensor nodes in the network [32, 110, 219]. The activities of the sensor nodes include transmission, reception, sensing, processing, and idle listening. Energy consumption can also be defined as the difference between the initial energy (IE) and the remaining energy (RE). Hence, the total energy consumption of a node is the sum of used transmit energy (ETX), receiving energy (ERX), sensing energy (ES), processing energy (EP), idle energy (EID), and sleep energy (ES).

According to our review, because SMAC is an energy-efficient MAC protocol for WSNs, most SMAC variants prioritized energy efficiency over delay, throughput, packet delivery ratio, and packet loss ratio, with 45%, 27%, 22%, 4%, and 3%, respectively (see Figure 11). Our findings indicate that future energy efficiency and throughput tradeoffs must be addressed.

5. Implementations of SMAC-Based WSN Applications

SMAC is an asynchronous duty cycle MAC protocol appropriate for monitoring applications that do not require SNs to transmit data regularly. Water quality monitoring (WQM), wireless body area network (WBAN), precision agriculture, climate change and pollution mitigation, water and sanitation, and many other applications are included

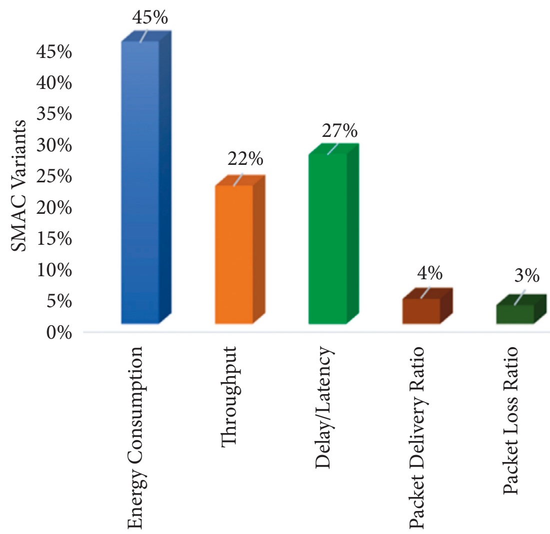

Figure 11: Distribution of performance metrics used in proposed SMAC variants.

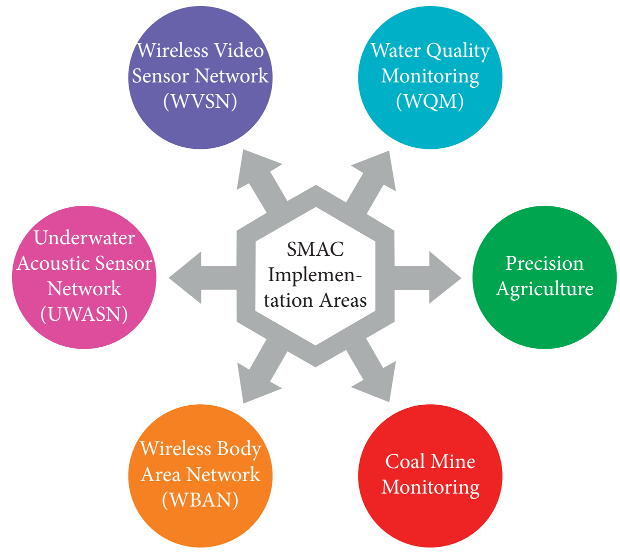

Figure 12: Implementation of SMAC in WSN applications.

[220]. As a result, we present some SMAC applications in WQM, WBAN, precision agriculture (PA), coal mine monitoring, underwater acoustic sensor network (UWASN), and wireless video sensor network (WVSN) (see Figure 12).

5.1. Water Quality Monitoring SMAC. Water quality monitoring is a WSN environmental monitoring application in which wireless sensor nodes are deployed in a body of water to monitor and detect changes in water quality. Temperature, pH, dissolved oxygen, and other water quality parameters prevent contaminated water supply [221–224]. Similarly, sensor nodes in WQM have energy consumption issues due to battery power limitations. Energy-efficient techniques and protocols have been proposed to address this issue, and SMAC is one of the promising solutions for the energy drainage of sensor nodes in WQM. A practical application of SMAC-based WSN for WQM has been demonstrated [225]. The authors used SMAC in their remote water quality monitoring application to reduce SN energy waste. The nodes were programmed to sleep for 12 seconds before waking up to communicate and check for water pollution. If a pollution event is detected, the wakeup time is reset to around 2 hours. The nodes can send event data to the gatherer, who aggregates the data from the nodes. As a result, the SMAC protocol is valuable and applicable in WSN applications.

5.2. Wireless Body Area Network (WBAN) SMAC. WBAN enables real-time and continuous monitoring in medicine, entertainment, sports, and military training where sensors are placed on or inside the human body [226]. WBAN typically consists of many lightweight battery-powered medical and nonmedical nodes placed on/around or implanted in the human body (Huang, Shan, & Shen, 2011). These battery-powered nodes collect physiological data such as temperature, heart rate, glucose, and more from the human body. They send it to a centralized node known as the coordinator or the gateway. Figure 13 shows WBAN architecture adapted from Crema et al. [227]. The gateway communicates with a base station (BS), which wirelessly transmits the data collected by the nodes to a remote computer [228]. However, battery-powered sensors, particularly implantable sensors, are difficult to remove and replace when the battery dies or wastes energy, causing harm to the human body. Due to high control packet, overheard, packet collision, over-emitting, over-hearing, and idle-listening, data transmission is the primary cause of energy waste in WBAN [229].

SMAC is used as a MAC layer protocol in WBAN to reduce energy dissipation caused by idle listening [132, 230]. SMAC is also used as a performance benchmark with other MAC protocols [231, 232] to compare the performance of SMAC's energy efficiency over proposed MAC protocols. Otoum et al. [233]; on the other hand, used SMAC in an epileptic patient monitoring system (EPMS). The EPMS was created to help reduce response time for immediate seizures and protect patients from severe consequences. In EPMS, the SMAC protocol was used as the MAC protocol in conjunction with a multipath routing algorithm to minimize delays and maximize system throughput. A 10% duty cycle was used alongside 1/10 syncFlag and selfConfigFlag. The EPMS simulation was carried out in NS-2 using SMAC and Zigbee. The simulation results showed that SMAC achieved the shortest end-to-end delay and the highest throughput compared to the Zigbee protocol. As a result, SMAC has been deemed the best and most appropriate MAC protocol for medical monitoring applications. Although SMAC is mentioned as an energy-efficient MAC protocol for WBAN, its implementations and design are inadequate compared to other MAC protocols. A fixed duty cycle does not accommodate current traffic load variations in WSN applications like WBAN.

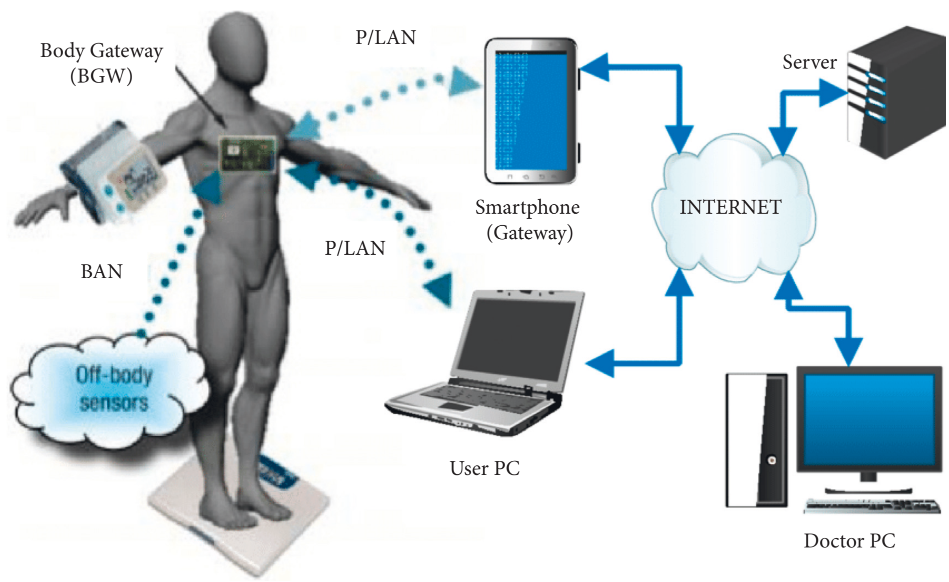

Figure 13: WBAN architecture.

5.3. Precision Agriculture SMAC. Unlike traditional agriculture, precision agriculture employs technologies to ensure that specific agricultural inputs such as irrigation, fertilizers, and medications are applied in the precise quantities required [234]. Precision agriculture reduces farmers' weeding, harvesting, sowing, and pesticide application workloads [235]. WSNs are used in precision agriculture by deploying sensor nodes to sense, monitor, collect, and measure various environmental parameters. Soil moisture, soil PH values, soil temperature, soil salinity, and soil humidity are measured parameters to improve the quantity and quality of agricultural produce [236, 237]. The sensor nodes are used for monitoring in the agricultural field. Similarly, sensor nodes rely on limited battery power for precision agriculture operations and face issues with energy consumption. To provide optimal solutions for WSN in precision agriculture, energy-efficient schemes such as sleep/wake schemes that include duty-cycling, MAC protocols, and topology controls have been proposed [235]. For precision agriculture, Ping Drowsy MAC (PD-MAC) was designed by Sahota et al. [234] to save energy during the wakeup synchronization phase in the MAC layer.

SMAC without RTS and CTS was also implemented as a performance benchmark for PD-MAC with no contention in its schedule. Because of SMAC's high overheads during its wakeup synchronization phase, the simulation results showed that PD-MAC consumed 65% less energy than SMAC. On the other hand, Lee et al. [238] used SMAC alongside X-MAC and LP-MAC (Link Quality based on Power MAC) protocols in their ubiquitous agriculture application to determine the best energy-efficient and low transmission delay MAC protocol in an agricultural site. With many nodes and small transmission packets, LP-MAC with a credible duty cycle of 22% proved to be the best energy-efficient MAC protocol over SMAC with a 22% duty cycle and X-MAC (16.3% duty cycle) [238]. Ndindiriyimana [220]; on the other hand, proposed an improved SMAC protocol that reduced the high energy consumption of border nodes that use multiple schedules for precision agriculture, giving SMAC the attention it required.

5.4. Industrial Environment SMAC. Shi et al. [112] developed a multi-WSN model based on SMAC for industrial environments. SMAC is typically used in industrial communication to reduce the energy consumption of sensor nodes. The time delay was specified in their model. Their model improved on the analytical model of Luo et al. [114], which lacked a network control model. As a result, Shi et al. [112] established a network controller based on network delay. The model was simulated to verify its accuracy and performance in a multihop industrial network versus a single-hop network. However, a model for energy consumption and throughput for practical performance evaluation was omitted.

5.5. Coal Mine Monitoring SMAC. WSN monitoring systems detect or sense pressure, flammable and poisonous gases in the coal mine, and track and protect underground miners from hazards or harmful accidents. Mobile and fixed WSN nodes, a base station, a console, and an information-gathering server comprise the coal mine monitoring system [239]. SMAC is a MAC protocol used in coal mine monitoring systems to control sensor node communication, synchronization, and energy consumption. However, the original SMAC is limited to the poor backoff algorithm, binary exponential back-off (BEB), which affects energy consumption, delay, and throughput due to the fixed contention window. As a result, Xuan-min and Shu-yuan [202] created an improved and adaptive backoff algorithm based on the current contention window (CW) and the channel state (i.e. either idle or busy) for a coal mine security monitoring and alarming system. The experimental results demonstrated that the improved SMAC protocol is more adaptable to traffic load, resulting in less delay and lower energy consumption than the original SMAC protocol.

5.6. Underwater Acoustic Wireless Sensor Network (UWASN) SMAC. Another WSN environmental monitoring application type is UWASN, which entails deploying sensor nodes to sense, collect, and monitor an aquatic environment in real-time for analysis and decision-making via a wireless medium. Although WSN performs admirably in UWASN, the limited battery power combined with difficult battery recharging makes energy dissipation difficult [240]. MAC protocols have been proposed in response to the activities that cause high energy dissipation in the MAC layer. However, limited bandwidth, propagation, and delay variance continue to be a problem in MAC protocols that require more exploitation [241]. Li et al. [131] evaluated SMAC, IEEE 802.11, and TDMA in the underwater acoustic channel based on bandwidth utilization, time-lapses, and energy consumption, where SMAC and IEEE 802.11 demonstrated more energy savings than TDMA.

5.7. Wireless Video Sensor Network (WVSN) SMAC. SMAC is a popular energy-efficient MAC protocol for WSN monitoring applications, but WVSN operates differently. SMAC was designed to support single-channel architecture, whereas WVSN employs MAC protocols that support multichannel architecture. SMAC also saves energy at the expense of end-to-end delay and throughput [242]. On the other hand, SMAC is used in WVSN as a performance benchmark for MAC protocols to measure energy consumption, throughput, and consumption [243]. Salim et al. [198]; on the other hand, improved the original SMAC protocol for WVSN. They created an improved SMAC to reduce long queue delays of critical or high-priority data, which slows down intrusion detection. As a result, priority bits indicate the importance of data that must be processed immediately after being queued. A priority bit of 0 indicated critical data, while a priority bit of 1 indicated noncritical data. The proposed protocols eliminated queuing delays for necessary data or frames for better surveillance and faster detection and processing of intrusions.

6. Open Issues and Future Research Directions

We have discussed MAC protocols for WSNs, SMAC-based WSN protocols, and improved SMAC protocols developed by researchers in the preceding sections. Additionally, we discussed SMAC's shortcomings and improvements and the various simulation tools, energy considerations, and performance metrics. Although several authors have proposed SMAC-based WSNs protocols as a well-known synchronous low duty cycle protocol that improves the 802.11 protocol, areas still require additional research. While discussing various MAC layer issues such as idle listening, packet overhearing, packet control, overheads, and packet collision, we focused on the potential benefits of using SMAC. The adoption of SMAC as an energy-efficient MAC protocol in WSN for environmental monitoring continues to face significant shortcomings.

The challenges posed by border node adoption, such as multiple schedules, fixed duty cycle, and increased end-to-end delay or latency, are still being addressed. Other challenges relating to fixed contention window or ineffective backoff algorithm, unnecessary idle listening, and high control overheads, in particular, are also receiving attention. Energy optimization, energy-efficient operation, robust support for high traffic loads, dynamic network traffic, and mobility are just a few challenges that require additional research. Additionally, issues specific to the SMAC implementation process must be addressed due to monitoring the environment's applications. Due to the dynamic nature of application environments, SMAC must optimize energy consumption to prolong the network's life. This section will discuss some of the open issues and future research directions that must be investigated to improve the performance and reliability of SMAC-based WSN systems.

6.1. Energy Harvesting SMAC. Energy harvesting (EH) has received considerable attention in recent research on energy-efficient WSN techniques. The energy harvested from the environment is typically weak (i.e. vibration energy harvesters, which produce low-power) and unstable (i.e. solar energy, which does not operate at night or in bad weather conditions), limiting them to coupling with low-power devices despite EH's exceptional effectiveness at supplementing sensor devices' limited battery power. Several MAC protocols have been proposed for incorporation into energy harvesting WSNs [244–248], but few of these works focus on SMAC. Tadayon et al. [249] used an analytical model to design and incorporate a solar energy harvesting model into SMAC to determine its performance in maximizing the network lifetime of wireless sensor nodes and developing an energy-efficient MAC protocol for energy harvesting-based WSN. The authors modelled solar energy harvesting in a PV cell to ascertain SMAC's higher throughput resulting from more significant bursts in the EH-based WSNs. Rao and Pillai [250] compared the energy consumption of SMAC and solar energy harvested from the sun. Several vital parameters such as duty cycle and data rates were considered to determine the applicability of SMAC in solar energy harvesting in WSN. Their findings indicate that the fixed duty cycle of SMAC makes energy harvesting impractical. Hence, future research should focus on designing adaptive duty cycle protocols suitable for satisfying the dynamic characteristics of current WSN monitoring applications. In addition, high-capacity devices for WSN applications must be compatible with low-cost, high-output EH equipment that is high in efficiency. Graphene is a new energy-storing material that enhances the performance of supercapacitors, Li-ion, Li-Si, and Na-ion batteries. SMAC's novel adaptive duty cycle protocols can be implemented with energy harvesting to evaluate SMAC's adaptability to exploit further and investigate issues that may arise in such implementations.

6.2. Robust Support for Traffic Load. Robust traffic load support is a critical design consideration for WSN MAC protocols. While SMAC has been shown to decrease the energy consumption of wireless sensor nodes, the fixed duty cycle, and contention window are insufficient for traffic adaptation. Issues that require urgent attention regarding traffic load include transmission control mechanisms, computation complexity, inadequate real-time application of protocols, and increased transmission power of broadcast messages. Because most protocols were limited to static application environments, future consideration should be given to mobile application environments. Additionally, configurable transmission power that requires fewer computations should be considered. While adaptive contention window/backoff algorithms facilitate traffic adaptation in SMAC, the complexity of traffic load prediction and maximum throughput continue to be open issues.

6.3. Energy-Efficient Operation and Optimization. SMAC is an energy-efficient MAC protocol, so its variants are primarily concerned with reducing sensor node energy consumption. Most proposed SMAC variants reduced energy consumption by addressing the border node problem, excessive idle listening, high control overheads, the backoff algorithm, and the fixed duty cycle. However, additional sources of energy waste, such as routing protocols, clustered networks, and data aggregation and acquisition, were overlooked. Further research should be conducted on SMAC's energy-efficient operation and optimization. The focus should be on routing protocols, clustered networks, network topological changes, data aggregation and acquisition techniques, and multihop and multipath network topologies that impact the network lifetime of WSN monitoring applications.

6.4. Heterogeneous and Multihop Networks. A heterogeneous network is made up of different sensor nodes that have other capabilities in terms of computation, energy, link, communication, and sensing range. The main advantages of heterogeneous networks are reduced latency and extended sensor node lifetime. Despite the growing interest in heterogeneous and multihop networks, most SMAC research has ignored heterogeneity in the pursuit of homogeneity. As a result, WSN for SMAC researchers should concentrate on heterogeneous network topologies that represent real-world applications involving heterogeneous sensor nodes. SMAC protocol design should also be tailored to heterogeneous networks, or it may become obsolete in current research. SMAC implementation is inadequate for multihop networks, and this must be addressed in future and recent studies.

6.5. New Network Topologies. Node deployment is a critical WSN design issue because it affects energy consumption, coverage, and connectivity. Depending on the network topology (bus, ring, mesh, star, and grid), it is necessary to critically examine the selected network topology and its effects on network performance. Most research in this area ignores the impact of network topology on energy consumption. Topologies such as star and bus contribute to high energy dissipation of sensor nodes, congestion, and packet loss. SMAC research should consider its application in other network topologies, such as grid and mesh, in the future. Grid topologies are energy efficient due to their multipath routing, which encourages clustering [251]. SMAC can thus be evaluated in clustered networks using grid topology simulation.

6.6. New Simulation Models. The latest WSN simulators, such as NS-3, OMNET++, and OPNET, have been updated, and new features and modules have been added. To help researchers perform simulations, SMAC should be implemented in these new simulators. According to studies, 66% of the work done to improve SMAC used NS-2 simulations. Because of the NS-2's obsolescence, the obtained results may lack accuracy and applicability in real-world monitoring applications; thus, researchers should consider updated simulators with features that reflect real-world environments for accurate results and applicability.

6.7. Dynamic Network SMAC Protocol Design. Most existing works have not considered the implementation of mobility models in SMAC. Mobility models are driving forces in current WSN research and applications. As a result, future SMAC research should consider various mobility models for mobile application environments to determine the applicability of SMAC in existing WSN monitoring applications.

7. Conclusion

This paper presents a survey of the current state of the art in SMAC-based WSN protocols. We began by describing the work done in SMAC to address the limitations of the traditional MAC protocol. Furthermore, we describe the low duty cycle MAC protocol for WSNs, focussing on the synchronous low duty cycle. While there have been many improvements in SMAC-based WSN over the years, as highlighted in this paper, some open issues require additional research to further use SMAC-based WSN for efficient adaptation in environmental monitoring applications. To our knowledge, no energy harvesting SMAC mechanisms have been discussed in this field. Energy harvesting is critical in environmental monitoring applications, so incorporating it into a SMAC-based WSN is critical.

Furthermore, energy harvesting techniques that can assist the sensor network in remaining operational for more prolonged periods should be investigated. Finally, SMAC implementation in heterogeneous and multihop networks should be designed to ensure extensibility, and SMAC in clustered networks should be examined to achieve improved energy efficiency. Addressing these difficulties would improve the overall performance and effectiveness of SMAC-based WSN applications, particularly in environmental monitoring.

Data Availability

No data were used in the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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