A Survey on Medium Access Control Protocols based on Synchronous Duty Cycle Approach in Wireless Sensor Networks

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Abstract
Wireless sensor networks (WSNs) are new generation of wireless networks which have many potential applications and unique challenges. Some of their most important problems are their limited resources, independent and autonomous operation and dynamic topology. Also, maximum of energy consumption into these networks is occurred when data transmission. In recent decade, researchers have been trying to improving the efficiency of these networks; such as improving the existent protocols and presenting new protocols, increasing the battery capacity, chip designing and radio equipment. In attention to the many applications and constraints of WSNs, designing appropriate protocols for signaling, Medium Access Control (MAC) and data routing have particular importance. In sensor nodes, the radio equipment are most energy consumption part; thus, energy management and appropriate usage of radio in WSNs is necessary. Data link layer operations such as MAC control using of the radio equipment. Therefore, the MAC methods of WSNs should doing following operations: organizing and controlling access to the transmission medium and having efficient energy consumption. The purpose of this paper is discussing on popular Synchronous Duty Cycle (SDC) based MAC protocols of WSNs. It leads to providing possibility of extending them; also, developing and designing new MAC protocols for WSNs. Finally, introducing and designing appropriate MAC protocols lead to energy efficiency and prolonged network lifetime.
Keywords:
Wireless Sensor Network (WSN); Sensor Node; Communication Protocol; Medium Access Control (MAC); Synchronous Duty Cycle (SDC).

1. Introduction

Wireless Sensor Networks (WSNs) are homogeneous or heterogeneous systems consist of many small devices, called sensor nodes, that monitoring different environments or tracking some objects; i.e. sensor nodes cooperate to each-others and combine their local data to reach a global view of the operational environment [1, 2]. In WSNs there are two other components, called "aggregation points" (i.e. Cluster-Heads deployment locations) and "base station" (i.e. the Sink deployment location), which usually have more powerful resources and capabilities than usual sensor nodes. Cluster-Heads (CHs) collect information from their associated sensor nodes, aggregate and forward them to the Sink to process gathered data [3, 4].

Wireless sensor networks must operate unattended in an autonomous way for a long time [1, 2]. Most of the existing WSN run with battery supplied nodes and in many cases battery replacement or re-charge is not possible. Scarce energy resource may result in a short lifetime, so that energy management that minimizes energy consumption and maximizes the network lifetime is crucial. Radio equipment is the most consuming element of a sensor node; for this reason the efficient use of the radio is mandatory in WSNs [2, 5]. Link layer operations such as Medium Access Control (MAC) govern the use of the radio equipment. As a result, along with organization of multiple accesses, MAC methods for WSNs must be energy efficient.

In other words, limitations such as energy, bandwidth, processing capability and high energy consumption by radio equipment when data transmission in WSNs, lead to conditions such as delay in accessing to the transmission medium and data transmission, network lifetime reduction, increasing the costs of these networks design and implementation and imposing extra costs to the WSNs like replacing the destroyed nodes. The proposed method to solving this problem is: designing and using of appropriate, simple and energy conserving communication protocols such as MAC for WSNs. So, the main discussed problem into this paper is high energy consumption by radio equipment while communication and data transmission into WSNs. To solving this problem, we should introduce with existent communication protocols such as Medium Access Control (MAC) protocols. Therefore, the purpose of this paper is discussing on existent Synchronous Duty Cycle (SDC) based MAC protocols of WSNs; thus, it presented some of most popular of these protocols, their algorithms, major advantage and disadvantage. It leads to providing possibility of extending them; also, developing and designing new MAC protocols for WSNs. Introducing and designing appropriate MAC protocols lead to energy efficiency and prolonged network lifetime. Also, by using of the considered algorithm it is possible to solving energy

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limitation and data transmission problems of WSNs. The rest of this paper is organized as: Section 2 expressed an overview of WSNs; Section 3 considers Medium Access Control (MAC) in WSNs; section 4 discussing about some of most popular WSNs' SDC based MAC protocols; section 5 expressed reached results and conclusion; and finally, future works, are drawn in section 6.

2. An Overview of Wireless Sensor Networks

Wireless Sensor Network (WSN) is a wireless network with following major features [1, 2]:

- Infrastructure-less;
- No public address, often (data-centric);
- Consists of many tiny sensor nodes;
- Nodes distribution along with high-density in operational environment;
- Insecure radio links;
- Different communication models:
    - Centralized/Distributed WSNs;
    - Homogenous/Heterogeneous WSNs;
    - Hierarchical/Flat WSNs;
- Limited resources of sensor nodes;
- Main application domains of WSNs: monitoring and tracking (as shown in Figure2);

In continue of this section, it is represented sensor node's architecture (by Figure1) and an outline of different aspects of WSNs, such as their characteristics, applications, architectures and vulnerabilities (according to Figure2).

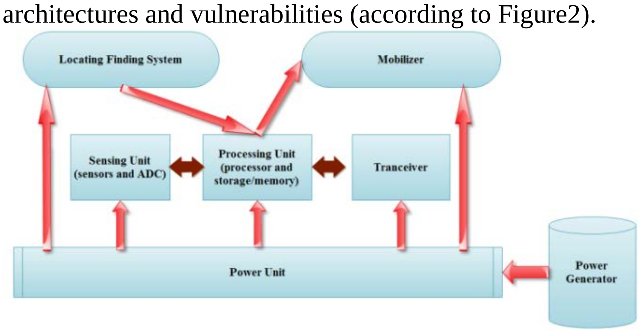

Fig. 1 Sensor node's architecture

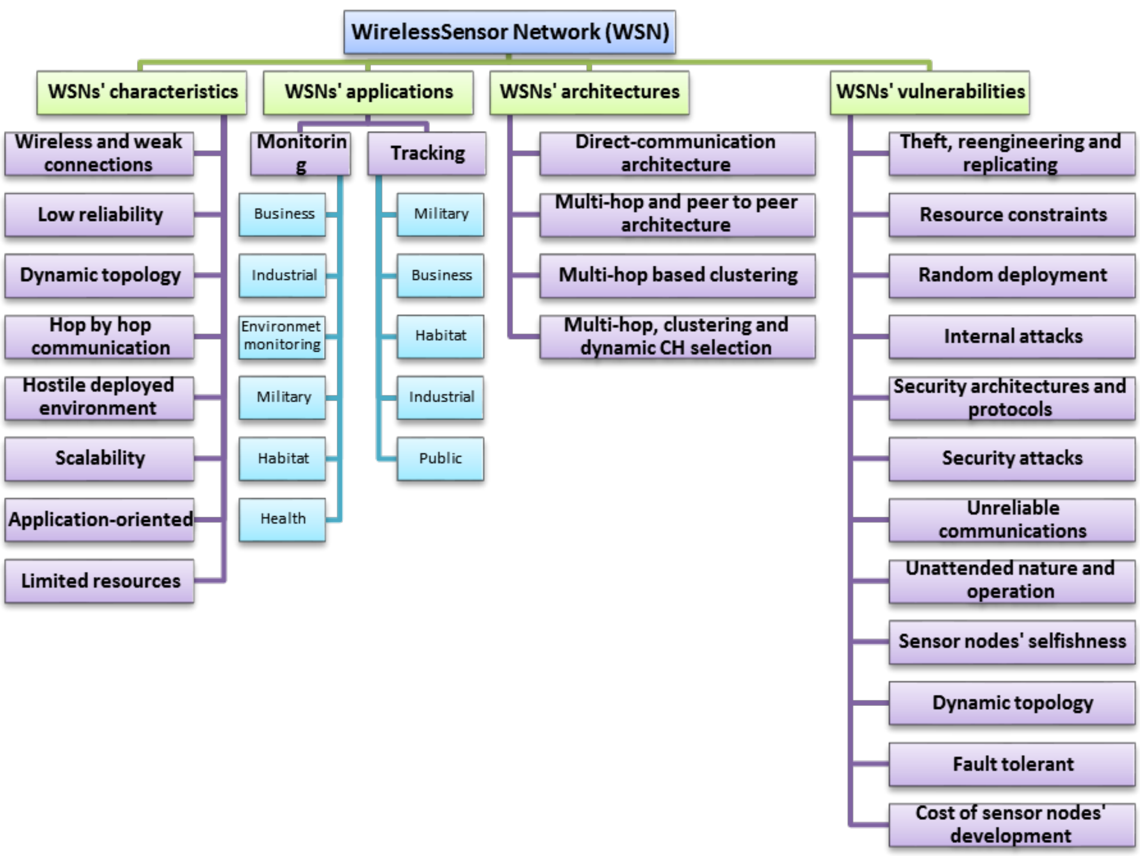

Fig. 2 WSNs' different aspects

3. Medium Access Control in Wireless Sensor Networks

The task of Medium Access Control (MAC) sub-layer of data link layer is providing possibility of optimal usage of communication channel and controlling channel access by nodes. In designing MAC protocols, there are different factors, like QoS (Quality of Service), throughput and energy efficiency; but, they are usually opposite together. So, designing MAC methods for WSNs is an important and complex problem. Limited processing resources and strong energy consumption constraints, require simple and energy conserving MAC methods for WSNs [3, 4, 5]. Moreover, a multitude of applications use WSNs; so, MAC methods must also be adaptive and flexible. In general, there are four MAC approaches, as following:

- Scheduling-based MAC approach

The main advantage of scheduling-based MAC protocols is the absence of collisions, idle listening and overhearing problems; as a consequence, the energy waste is limited. However, the cost of organizing channel access of nodes at the network level may be prohibitive in WSNs with stringent energy constraints [5, 6]. This MAC approach is allocating a piece of channel access to each node, on a permanent basis. Such piece of channel access can be a time slot in TDMA[1]-like protocols, a frequency band in FDMA[2]-like, a code in CDMA[3]-like protocols or a combination of these elements.

- Synchronous Duty Cycle (SDC) based MAC approach

The second approach's goal is synchronizing nodes on a common sleep/wakeup scheduling program; to do so, short synchronization messages are periodically exchanged between nodes [6].
The goal of this approach is coordinating node wake-ups and sleep periods to achieve a synchronous duty cycle. Communication is concentrated during active periods so that energy waste due to idle listening is limited. Nodes alternate simultaneous active and inactive periods; therefore, this approach requires the node to be synchronized at network level.

- Random MAC protocols

In the third approach, node sleep/wake-up schedules are independent and not synchronized. Each node follows its own schedule that consists in sleeping most of the time and sensing the channel with a given periodicity. A node that has data waiting in its packet queue transmits a long preamble frame prior to sending data. The time duration of a preamble must be long enough to cover two consecutive wake-up instants of a potential receiver [5, 6]. The synchronous preamble sampling combines the last two approaches. Nodes make use of very short preambles and require tight synchronization between each other. So, random access protocols easy apply to WSNs and energy efficient, due to the absence of signaling messages for channel access synchronization. The lack of synchronization results indeed in limited protocol overhead; however, it may severely expose nodes to problems such as idle listening, overhearing, and collisions. There are several groups of random-based MAC protocols, such as:

- Preamble Sampling (PS) class;
- Carrier Sense Multiple Access (CSMA) class;
- Multiple radios class;
- Hybrid MAC approach;

This paper has been focused on SDC-based MAC approach and its protocols. In continue, this section represented different dimensions of MAC in WSNs (according to the Figure3).
In continue, SDC-based MAC approach in WSNs and its various popular protocols will be considered. For each of the discussed protocol, it will be expressed its algorithm, characteristics, main advantages and disadvantages.

4. Synchronous Duty Cycle (SDC) based Protocols in Wireless Sensor Networks

The protocols of this kind aim at coordinating node wake-ups and sleep periods to achieve a synchronous duty cycle. Communication is concentrated during active periods so that energy waste due to idle listening is limited. Nodes alternate simultaneous active and inactive periods; therefore, this approach requires the node to be synchronized at network level.

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

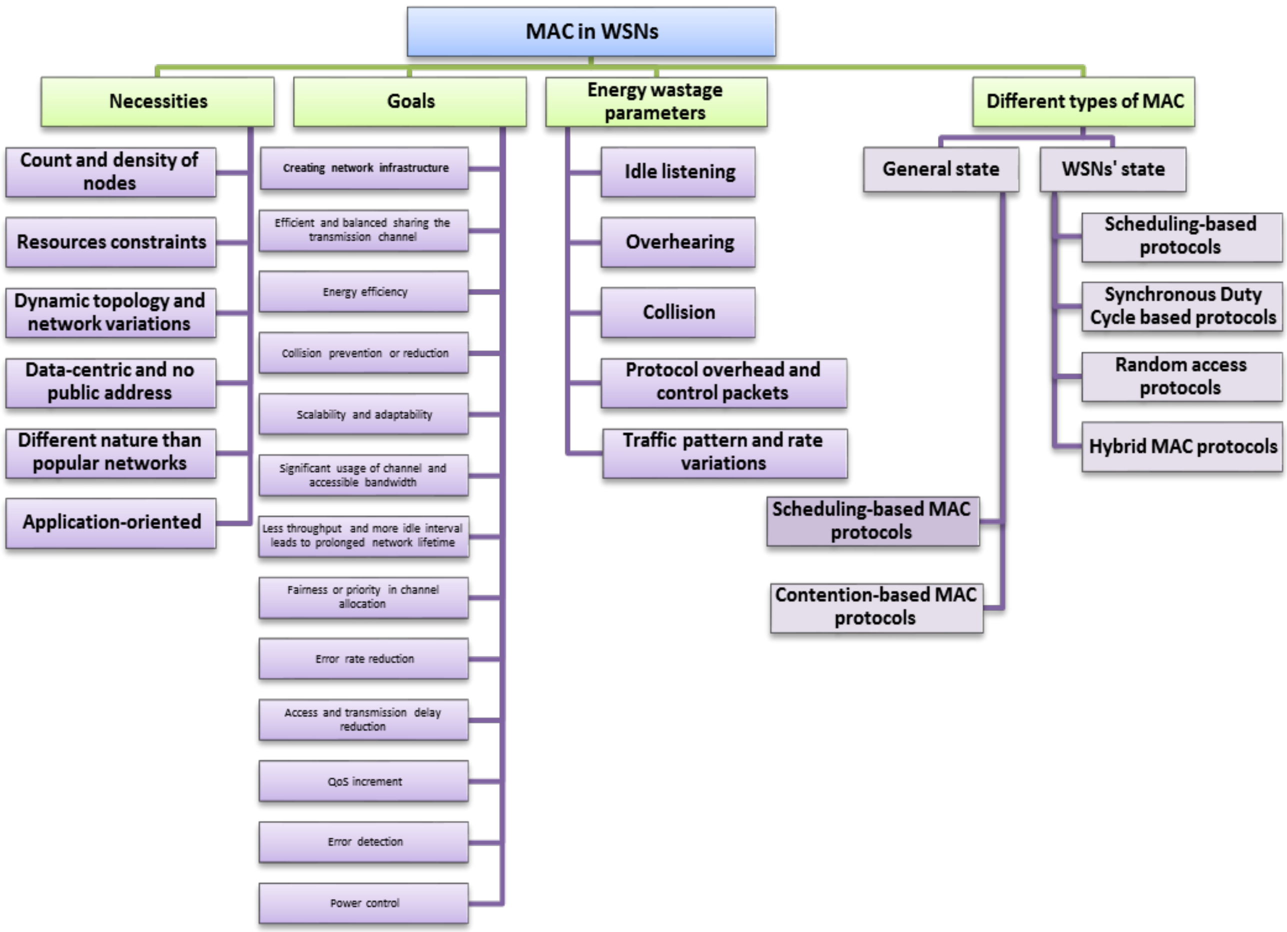

Fig. 3 Different dimensions of MAC protocols in WSNs

The network is divided in virtual clusters (VC) in which nodes have the same wake-up/sleep schedule. If two nodes have different schedules, i.e. those nodes belonging to two different VCs and then, they are unable to communicate. To maintain a fully connected network, boundary nodes are used to connect different VCs. To connect two VCs, boundary nodes must follow both schedules. Nodes of the same VC need to be synchronized to avoid time drift between each other. Synchronization procedure requires long periods in which all nodes exchange their schedule, then it is periodically updated using SYNC packets sent during the active period. When multiple nodes want to transmit to the same destination, they wait for the node to wake up and run a CSMA/CA procedure with Request-To-Send (RTS), Clear-To-Send (CTS), data and acknowledgment (ACK) messages exchange. When a long message has to be sent, it can be fragmented and sent as a burst, which avoids repeating the RTS/CTS handshake per each packet and waste energy.

Periodic and synchronous sleep/wake-up schedules result in sleep delays due to the need for nodes to wait for the next active period to send data.

Major properties of this protocol are as following:

- Nature: based on synchronous duty cycle
- Basis protocol: it is as a basic standard in synchronous duty cycle-based MAC methods
- Released year: 2002
- Mobility supporting: Yes

4.1 T-MAC Protocol[4]

The T-MAC protocol [8] is an evolution of S-MAC in the sense that it proposes an adaptive duty cycle. T-MAC adopts the same synchronization method of S-MAC and nodes are organized in virtual clusters as well. The main difference with respect to the S-MAC protocol is that the active period has variable duration depending on the real needs of the node. Using a variable active period permits to reduce idle listening; because if no communication is going on, nodes can immediately turn the radio to sleep

[4] Time-out MAC (An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks)

mode; thus reducing its active period. The amount of energy savings depends on the amount of time removed from the initial active period. As S-MAC, the T-MAC protocol must face the problem of early sleeping that causes sleep delays. To solve this problem, nodes use Future-RTS (FRTS) frames to inform nodes that are two hops away which a message will be sent very soon; so that, they wait before going back to sleep. Along with energy saving, other consequences of adaptive active period and FRTS messages are: increased latency and decreased throughput. To guarantee that nodes do not miss useful communications after the SYNC period, they have to wait a timeout that should be appropriately set. If during the timeout nothing is sensed, the radio can be turned off until the next frame.

Major properties of this protocol are as following:

- Nature: based on synchronous duty cycle
- Basis protocol: the S-MAC protocol
- Released year: 2003
- Mobility supporting: No

4.2 S-MAC/AL Protocol[5]

The S-MAC/AL protocol [9] solves this problem: if nodes overhear neighbor messages, they can learn the instant at which they will end their transmission and clear the channel; then, they all turn their radio to sleep mode and wake up when channel will be clear (even though this happens during a sleep period) to exchange messages.

Major properties of this protocol are as following:

- Nature: based on synchronous duty cycle
- Basis protocol: the S-MAC protocol
- Released year: 2004
- Mobility supporting: No

4.3 MS-MAC Protocol[6]

The MS-MAC protocol [10] is an evolution of the S-MAC protocol with supporting mobile environments.
In S-MAC protocol, all members of a virtual cluster periodically perform a neighbor discovery procedure to discover new nodes. Neighbor discovery consists in keeping their radio in listening mode for duration of around 10 seconds to detect possible messages of any unknown source.
The innovation of MS-MAC protocol consists in adapting the period of neighbor discovery procedure and making it dependent on the mobility degree of nodes. In MS-MAC protocol, nodes are not supposed to know their position; thus, they do not estimate their mobility; nevertheless, by using of the variation of received signal strength of SYNC packets, they are able to detect if a neighbor is moving or not. When a node detects mobility of a neighbor, it also registers the variation of the received signal strength; so that its speed can be evaluated. In the case of multiple moving neighbors, the period of discovery procedure is adapted with respect to the fastest node. When a node adapts its schedule to mobility of neighbors, it adds mobility information inside its next SYNC packets (max estimated speed among all neighbors), so that all neighbors can update their periodicity and keep the cluster synchronized.
In the MS-MAC protocol, when one node moves, its neighbors create an active area around it by adapting their wake-up schedule as a consequence. The advantage of this procedure is that when a node moves from a virtual cluster to another one, the time spent while disconnected from the network is limited. As a counterpart, the short time that each mobile node spends disconnected is paid in terms of consumed energy of its neighbors that must remain awake for a longer time.

Major properties of this protocol are as following:

- Nature: based on synchronous duty cycle
- Basis protocol: the S-MAC protocol
- Released year: 2004
- Mobility supporting: Yes

4.4 D-MAC Protocol[7]

The D-MAC protocol [11] works for WSNs supporting converge-cast communications; that is, with D-MAC all traffic generated by nodes must be unidirectional and must converge to a unique sink node. The resulting network topology is a tree rooted at the sink. In D-MAC, wake-up instants of nodes are shifted with respect to the others depending on the position in the routing tree. In particular, each node in the tree has its active period that partially overlaps the active period of its next-hop and partially the active period of its previous node. In this way, a message can be forwarded from the source to the sink without any delay. Although efficient with converge traffic directed to one sink, the D-MAC may suffer from network dynamicity such as mobility of nodes and different traffic patterns.

Major properties of this protocol are as following:

- Nature: based on synchronous duty cycle
- Basis protocol: the S-MAC protocol
- Released year: 2004
- Mobility supporting: No

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[5] S-MAC with Adaptive Listening (S-MAC/AL) (Medium Access Control with Coordinated, Adaptive Sleeping for Wireless Sensor Networks)

[6] An Adaptive Mobility-Aware MAC Protocol for Sensor Networks (MS-MAC)

[7] Data gathering MAC (D-MAC)

4.5 EKF Protocol[8]

In EKF protocol [12], nodes of each transmitter-receiver couple are capable of computing their relative speed and the effect of the Doppler shift (absolute position and speed are estimated). So, they can predict the optimal frame size that keeps Packet Error Rate (PER) under a given threshold and adapt it as a consequence. The optimal frame size is inversely proportional to the relative speed of the transmitter-receiver couple.

Major properties of this protocol are as following:

- Nature: based on synchronous duty cycle
- Basis protocol: the S-MAC protocol
- Released year: 2005
- Mobility supporting: Yes

4.6 R-MAC Protocol[9]

The R-MAC protocol [13] is a synchronous duty cycle MAC method which exploits routing information to reduce latency in multi-hop sensor networks. Nodes are assumed synchronized and each cycle is divided in three periods similarly to S-MAC protocol:

- Synchronization period;
- Data period;
- Sleep period;

The period that differs from S-MAC protocol is the Data period; when a node wants to send data, it previously sends a PION message (Pioneer frame) to its intended receiver to announce its data transmission. If the receiver is not the final destination of the packet, this last node immediately sends another PION to its next-hop and so on, until a predefined count of hops (similarly to FRTS used in T-MAC protocol). This way each packet can be forwarded multiple times during the same operational cycle.

Major properties of this protocol are as following:

- Nature: based on synchronous duty cycle
- Basis protocol: the S-MAC protocol
- Released year: 2007
- Mobility supporting: No

4.7 DW-MAC Protocol[10]

The DW-MAC protocol [14] is a synchronous duty cycle MAC which its goal is solving the problem of packet forwarding in multi-hop networks. Like in R-MAC, when a message needs to be sent, the sender wants to alert several nodes in the path toward the final destination to prevent them from going to sleep, too early. In DW-MAC protocol, medium access control and scheduling are coupled. Sender and receiver are able to agree to the time instant at which data packet must be sent just by sending/receiving the control message, called SCHEDULE message. As S-MAC and partially also T-MAC and R-MAC, the DW-MAC protocol suffers from the forwarding interruption problem, which it is solved in D-MAC protocol by perfect synchronization of nodes.

Major properties of this protocol are as following:

- Nature: based on synchronous duty cycle
- Basis protocol: the S-MAC protocol
- Released year: 2008
- Mobility supporting: No

5. Conclusions

According to this research, the major reasons of energy wastage in WSNs are as following:

- Idle listening: the activity of polling the channel without the reception of any frame;
- Overhearing: the activity of receiving a frame that is destined to someone else;
- Collision: re-transmissions of frames that may occur when two receptions overlap in time;
- Protocols' overhead and exchanging control packets;
- Traffic pattern variations;

Thus, while organizing channel access, the MAC protocol for WSN must be energy efficient. To save energy, the goal of devices is achieving low duty cycles; i.e. they alternate sleep periods and active periods. During active periods, nodes exchange frames to communicate while during sleep periods, radio is switched off. The challenge of MAC is to coordinate active periods so that when there is a frame to send, transmitter and receiver wake up, communicate and go back to sleep.

Coordinate active periods in large, dense and multi-hop networks is a complex problem. Existent solutions basically adopt four approaches, including of:

- Scheduling-based protocols;
- Synchronous Duty Cycle (SDC) based protocols;
- Random access protocols;
- Hybrid protocols;

This paper has investigated main contributions of Synchronous Duty Cycle (SDC) approach of MAC protocols and providing their algorithms, strong aspects and drawbacks.

Following table (Table1) is showing popular SDC-based MAC protocols of WSNs and comparing them together in terms of their nature, basis protocols, released year and

[8] S-MAC with Extended Kalman Filter protocol (EKF): A Mobility Based Link Layer Approach for Mobile Wireless Sensor Networks
[9] Routing MAC (R-MAC): A Routing-Enhanced Duty-Cycle MAC Protocol for Wireless Sensor Networks
[10] Demand Wake-up MAC protocol (DW-MAC protocol)

mobility supporting. Also, Table2 and Figure4 are representing some of most important statistical information about this research; they say, this paper have been considered eight SDC-based MAC protocols of WSNs; three protocols of them supporting from mobile operational environments (about 37.50 percentage); one protocol of them is independent and not inspired from other protocols (about 12.50 percentage); also, about 87.50 percentage of considered protocols are extended and inspired protocols.

Table 1: A comparison of SDC-based MAC protocols of WSNs

No.	MAC protocol	Basis protocol[11]	Release year	Mobility nodes supporting
1	S-MAC	Independent	2002	Yes
2	T-MAC	S-MAC	2003	No
3	S-MAC/AL	S-MAC	2004	No
4	MS-MAC	S-MAC	2004	Yes
5	D-MAC	S-MAC	2004	No
6	EKF	S-MAC	2005	Yes
7	R-MAC	S-MAC	2007	No
8	DW-MAC	S-MAC	2008	No

Table 2: Statistical information about SDC-based MAC protocols of WSNs

Property	Total frequency	Frequency of mobility supporting	Mobility supporting percentage	Frequency of independent protocols	Frequency of extended protocols	Percentage of independent protocols	Percentage of extended protocols
	8	3	37.50	1	7	12.50	87.50

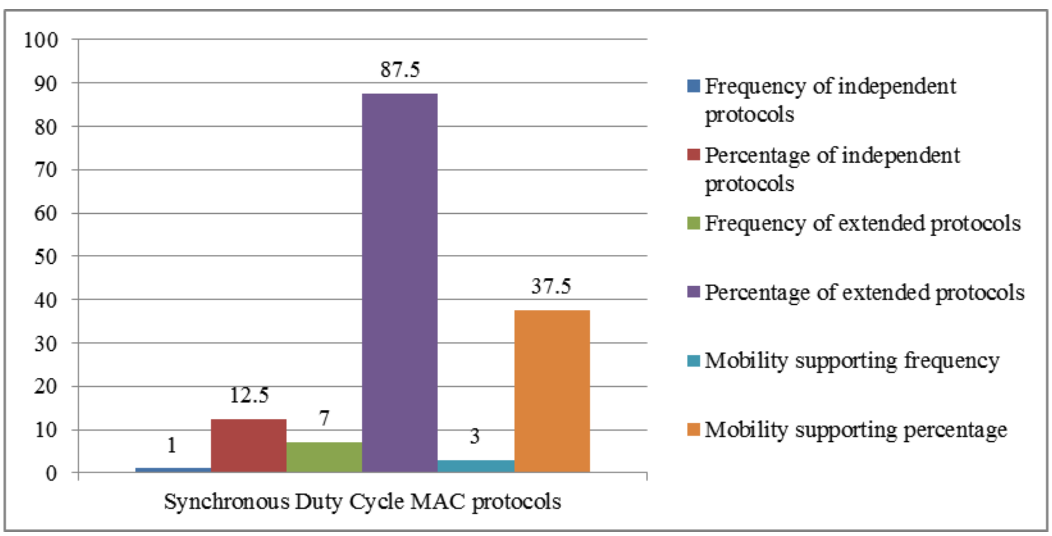

Fig. 4 A statistical comparison of mobility and undependability features of SDC-based MAC protocols of WSNs (in frequency and percentage)

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

It is hope this paper be useful in introducing with SDC-based MAC protocols of WSNs and creating a light way toward extending existent protocols or proposing new MAC protocols according to the WSNs' special characteristics and properties of each operational environment.

6. Future Works

There are several additional issues should be further studied in future research. Some of the most challenging and proposed topics of these issues are including of:

- Proposing new MAC techniques for WSNs;
- Presenting an energy-efficient and light-weight MAC protocol;
- Presenting a light-weight error detection and error correction algorithm and integrating it with the MAC protocol;
- Proposing new proper criteria for controlling the medium access in WSNs;
- Designing a light-weight data compression and aggregation algorithm for using before accessing to the communication channel;
- Presenting a survey about scheduling-based MAC protocols of WSNs;
- Presenting a survey about random MAC protocols of WSNs;
- Presenting a survey on hybrid MAC protocols of WSNs;

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