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Energy Efficient Duty-Cycled MAC Protocols for Wireless Sensor Networks

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Abstract: Ubiquitous nature of WSN paved way for its usage in different environments. Its applications are growing to many fields in the world. In such networks, there are many issues and challenges to be addressed. For instance, they are energy constrained networks with mobility that need energy efficient mechanisms. Especially MAC is the protocol that needs enhancement for different WSN deployments. In traditional deployments, it is to support multi-user access to same channel while in duty cycled networks it needs to achieve rendezvous to have energy efficient communications. Duty cycled networks are crucial for many applications like wind turbines where cyclical channels are used. Such networks need rendezvous for communication and thus traditional MAC is not suitable there. In this paper, we focused on different MAC protocols in different deployments modes. In other words, duty cycled MAC protocol are studied. It provides useful insights and directions for future work in implementation of new MAC protocols.

Keywords – Wireless Sensor Network (WSN), Medium Access Control (MAC), and duty cycled network, dynamic cyclical channel

I. INTRODUCTION

Wireless Sensor Network (WSN) is a network made up of sensor nodes. Such networks are deployed in civilian or military environments. The purpose of WSN is to gather data related to temperature, heat, light, pressure and so on. It has many applications like assisted living, monitoring household, military surveillance and environment monitoring to mention few [3]. Sensor nodes have constrained resources like 8MHz processing power, few hundred KBs storage and battery supplied energy. As nodes have limited energy sources, it is very important for WSN to save energy for increasing its life span. In the contemporary era, WSN plays vital role as it can be integrated with Internet of Things (IoT) technology. Thus it can become part of many real world IoT use cases or smart applications. A typical WSN appears as in Figure 1. However, duty cycled WSN deployments may have customized models.

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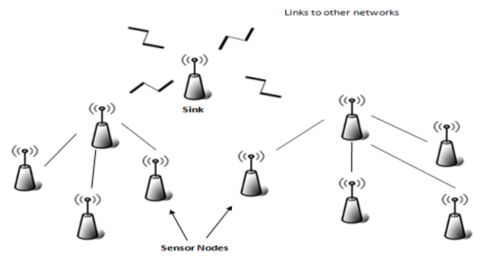

Figure 1: A typical WSN with sensor nodes and base station or sink

WSN can be used in many environments and applications. The utility of WSN can be realized in entertainment, environment monitoring, industrial applications, smart buildings, climate control, smart grids, energy control systems, precision agriculture, security, surveillance, animal tracking, healthcare monitoring, smart transportation, logistics, monitoring of civil structures and urban terrain tracking. WSN has support for many topologies. They are called as mesh, star and tree. In star topology nodes can be connected directly to base station. Generally nodes do not have communication among themselves. There is communication between base station and remote nodes. A cascaded form of star topology is known as tree topology. Each sensor node is connected to a node higher to it in the path to reach base station. With tree topology expansion of network becomes easier besides detecting errors. The mesh topology helps nodes to communicate with other nodes in the given communication range. A node can receive and forward data to other nodes thus acting as transceiver. Different kinds of WSN are available based on their purpose. They are known as underground WSN, underwater WSN, terrestrial WSN, multimedia WSN and duty cycled WSN. All these are self-descriptive. With respect to duty cycled network is the network in which both sender and receiver will come in contact with each other at specific time in order to improve communication efficiency and reduce energy consumption.

Our contribution in this paper include the discussion of different duty cycled WSNs where different MAC protocol implementation is provided. Therefore, this paper focuses on different MAC protocols that are used in cyclical channels. The remainder of the paper is structured as follows. Section 2 provides details of MAC layer in OSI reference model. Section 3 provides the details of duty cycled protocols. It covers both synchronous and asynchronous networks. Section 4 provides summary of the important MAC protocols. Section 5 concludes the paper besides providing directions for future scope of the research.

II. 2. ABOUT MAC LAYER OF OSI REFERENCE MODEL

International Standards Organization (ISO) gave a reference model for networks. It is known as Open Systems Interconnection (OSI). It is meant for providing protocol standards that are useful in different network layers. Radio frequency channels are typically used by nodes in WSN as their physical medium. It actually corresponds to the bottom most layer of the model. As the nodes are to be connected physically, network based on OSI reference model provides data connectivity and also user mobility.

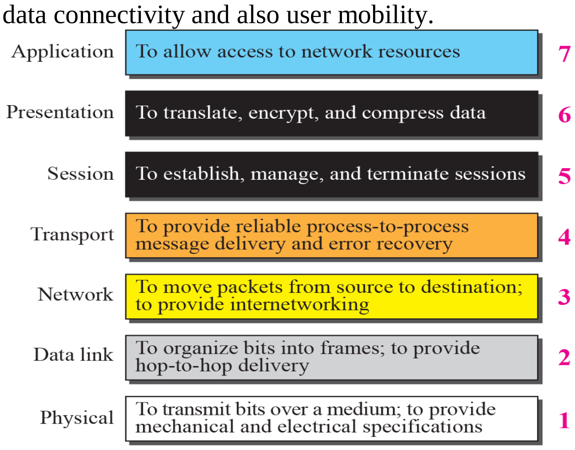

Figure 2: OSI reference model

As presented in Figure 2, different layers are there in the reference model. The layers include they physical layer, the data link layer, the network layer, the transport layer, the session layer, the presentation layer and the application layer. The application layer provides access to network resources. The presentation layer takes care of data translation, encryption and compression. Session layer on the other hand is for establishing and managing sessions. Transport layer takes care of message deliver and error recovery. Network layer on the other hand take care of data transfer among nodes and supports inter-networking. Data link layer is meant for organizing bits into frames and support hop-to-hop delivery. The physical layer is to have specifications actual data transfer over medium.

The IEEE 802.11 MAC layer is part of data link layer of OSI model. Data link layer is responsible to provide error free data transmission. In fact data link layer has two sub layers. They are known as Medium Access Control (MAC) and Logical Link Control (LLC). Error and flow control is provided by LLC while the MAC interfaces with the PHY layer for different services like medium access control, addressing and framing. The MAC layer enables movement of packets to and from a Network Interface Card (NIC) to another NIC over a shared channel. Traditional MAC protocols allow many users to access same channel at a time. However, a duty cycled MAC protocol arranges rendezvous. It does mean that the MAC protocol specifies a time and place where sender's and receiver's radio are on the communication can take place. More details on duty cycled MAC protocols are provided in the section 3.

III. 3. DUTY CYCLE BASED MAC PROTOCOLS IN WSN

This section provides energy efficient duty cycled MAC protocols designed for WSN. Low duty cycle MAC protocols became very useful as they can reduce power consumption and improve efficiency in WSN. Any low duty cycle protocol is able to reduce the idle time of a node. In other words, a node is not allowed to be idle or spending time in unnecessary activities like overhearing. Such nodes are kept in sleep mode in order to save energy and reduce idle time. When the nodes are in sleep mode, their radios are off. There will be rendezvous (specific place and time) enabling radio and complete communication. The low duty cycled MAC protocols are categorized into two types. They are known as synchronous low duty cycle MAC protocols and asynchronous low duty cycle MAC protocols.

3.1 Synchronous Low Duty Cycle MAC Protocols

In these networks there are pre-determined wakeup schedules for data exchange between source and destination nodes. The nodes are in sleep mode except when they are having wakeup schedules. Each node will send a beacon to other nodes to indicate that it is active. Thus all the will come to know the wakeup schedules of other nodes and perform data transfer accordingly. Typical periodic wakeup scheme is as in Figure 3.

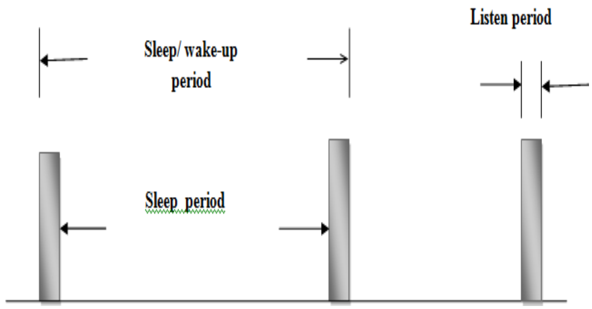

Figure 3: Illustrates periodic wake-up scheme

A node can have listen period and sleep period. The demarcation of the two periods can provide pre-defined duty cycles for saving energy and improve efficiency of WSN. When the sender and receiver nodes do have specific pre-determined rendezvous for communicating, it is known as synchronous low-duty cycle or wake-up scheme. It is illustrated in Figure 3.

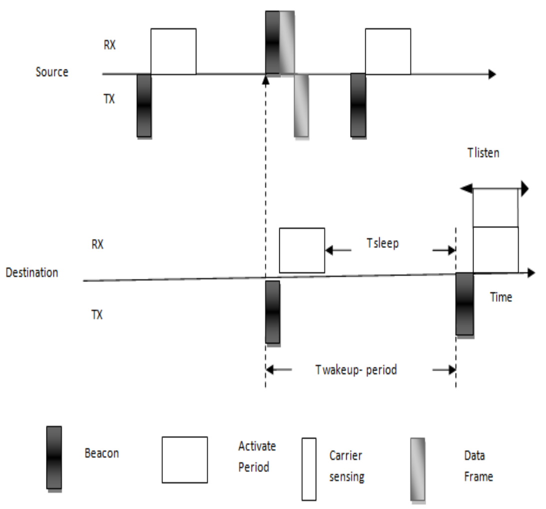

Figure 3: Synchronous low duty cycle wakeup scheme

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There is specific communication between source and destination nodes. There is beacon framework between source and destination. There is active period in which two nodes are involved in communication. There is carrier sensing and data framework exchange. When source node has to transfer data to destination node, it needs to wake-up as per schedules and then transmits its packets to destination node. As the wake-up cycles are known, it is possible that source and destination nodes only transmit data only at pre-determined time. Synchronization is typically use in small WSNs while large ones throw challenges such as scalability problem.

3.1.1 Self Organizing Slot Allocation (SOSA)

The Self-Organising Slot Allocation (SOSA) is the MAC protocol. It is an improved form of LEACH MAC. It has improved performance in terms of network scalability and energy efficiency. SRSA is basically a TDMA-based protocol that shares similar topology with LEACH protocol. It makes use of many base stations in order to improve energy efficiency as provided in the LEACH architecture. The cluster head (CH) is able to communicate with nearest base station directly. This will minimize transmission energy consumption as much as possible.

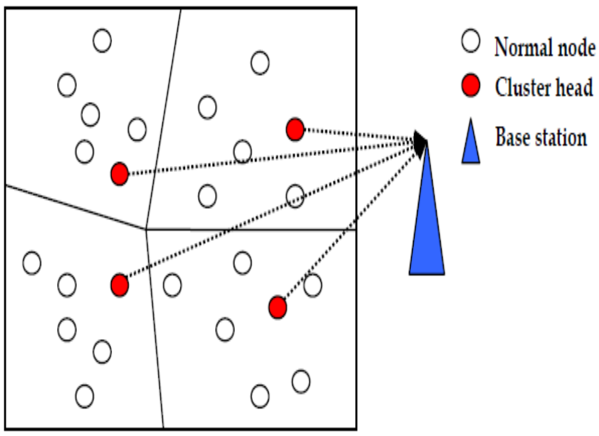

Figure 3: Clustered LEACH MAC

It also has scalability advantage. Towards this end it has feature of local synchronization in which a cluster uses local TDMA MAC frame. The reason behind initiating communication with an initial random TDMA is that it can adaptively perform slot change in allocation and also schedule locally as per the feedback obtained from perceived collisions exhibited by local nodes of the cluster. Local synchronization is thus helping in achieving scalability. However, if that happens frequently, it may lead to wastage of energy and cause issues to its performance.

3.1.2 Sensor-MAC (S-MAC)

S-MAC or Sensor MAC makes use of periodic sleep time. It is on top of virtual cluster features. The network uses single hop topology where S-MAC makes use of single frequency channel for communication. The period at which sender and receiver are active is set to 115ms. However, the wake-up time may be hundreds of milliseconds. Thus it has adjustable sleep period. In presence of clustering, the nodes are synchronized in such a way that they are wake up at given time. Again there are three phases in the active period namely SYNC, RTS and CTS. Each phase is further divided into some time slots. Each node makes use of CSMA mechanism with random back-off. This is used to have the SYNC, RTS and CTS packets to be sent to intended receivers and neighbours. From its neighbours, each node is capable of learning and sharing sleep schedule. Once SYNC phase is completed, a node that is supposed to transmit data has to contend for the channel. A node receives RTS or CTS packet after listening to channel. If the node is not intended receiver, it learns about the Network Allocation Vector (NAV) before entering into the sleep mode. During the phases of RTS and CTS a node can involve in both reception and transmission of data.

S-MAC's duty cycle mechanism makes it to have higher latency. The reason behind this is that, transmitter needs to wait till next cycle arrives in order to send data. To reduce latency in S-MAC is improved further to have adaptive listening. In the improved form of the network, the nodes that contain information on NAV wakeup when there is time for expected data transmission to be finished. Thus nodes do not wait for long time for incoming packets. Therefore with the introduction of adaptive listening to S-MAC, the latency is reduced to half. However, it causes more energy to be used as there is active part that is kept idle because of overhearing or non-activity.

3.1.3 Timeout-MAC

The T-MAC protocol is a variant of S-MAC protocol containing adaptive listening. It is meant for reducing or adjusting active period based on the prevailing traffic conditions at runtime. Therefore, there is no need for a node to be idle for the entire active period once SYNC phase is completed. This is useful when there is no activity found in the network. The T-MAC is formed as a single hop-hop topology and uses a single frequency channel for communication. Once CTS phase is carried out, for each receipt of frame, a node needs to wait for some time causing timeout window. If there is no activity detected and there is timeout occurred, the node goes to sleep mode. T-MAC is more energy efficient as it uses one-fifth of the energy consumed by S-MAC. Though power efficiency is increased, it leads to increased latency. In addition to this, T-MAC is not recommended for networks where there is high traffic and low latency is expected.

3.1.4 Zebra MAC (Z-MAC)

The Z-MAC protocol gains benefits of both TDMA and CSMA. Its network is made up of flat multi-hop topology. The nodes of the networks are fixed at different locations. In the setup phase, the concept of neighbour discovery is taken place. It also includes exchange of local frames and assignment of slots. A global time is used for synchronization. A slot is allocated to each node and that is fixed. Nodes in the network can contend for channel within any time slot. This is done for transmission of data. However, highest priority is given to assigned node. In the presence of high contention, slot assignment is exercised in order to reduce collisions. A long preamble is followed by data transmission.

This is made to increase probability of exploiting the active period of the receiver. High latency is exhibited by Z-MAC. It also showed high power usage due to long preamble transmission. As the nodes are fixed, it leads to limitations in scalability. When new node joins the networks, it is required to repeat the setup phase.

Table 1: Summary of synchronous duty cycles MAC protocols

Protocol Name	Target Applications	Key Design Principles	Strengths	Weaknesses
S-MAC	Multi-hop and bursty event applications.	Low duty cycle is fixed. Support for virtual clustering Uses either physical or virtual carrier sense It can also make use of randomized carrier sense time RTS/CTS and NAV are used for getting rid of overhearing.	Saves energy with low duty cycles. Scalability and self-configuration are supported with virtual clusters. Overhearing is avoided and saves energy. Contention latency is achieved with message passing	Periodic sleep causes high latency. As duty cycle is fixed, it is not adaptive when dynamic traffic is encountered.
T-MAC	Multi -hop and Supports dynamic traffic loads.	Burst of variable length messages are transmitted. With dynamic and adaptive duty cycle with timeout concept is supported. Supports the concept of Future Request to Sent (FRTS). Priority with threshold control.	With adaptation to traffic dynamically, it can save energy significantly.	Throughput is reduced and latency is increased with ADC. A live WS's communication pattern cannot be distinguished easily.
Z-MAC	Multi-hop applications.	Support for TDMA Support for CSMA Slot assignment is used to reduce collisions.	Takes benefits of CSMA and TDMA. Slot assignment is used to reduce collisions.	High power consumption due to the usage of long preambles.
SOSA -MAC	Multi-hop application	Variant of LEACH MAC.	Network scalability and energy efficiency.	Local synchronization may lead to wastage of memory.

As shown in Table 1, the summary of various synchronous duty cycles MAC protocols is presented. The protocols include T-MAC, Z-MAC, S-MAC and SOSA-MAC.

3.2 Asynchronous Low Duty Cycled MAC Protocols

This section provides various low duty cycled protocols. They are asynchronous MAC protocols that work in cyclic channels in different WSN deployments.

3.2.1 Wireless Sensor MAC (WiseMAC)

Wireless Sensor MAC is developed for reducing overhead caused b long preamble packet transmission. It gets rid of such thing from sender side and also handles collision probabilities. WiseMAC has two kinds of nodes in the network. They are known as ordinary sensor nodes and access points. Sensor nodes are supposed to communicate with access points. The network is formed with star topology. WiseMAC makes use of one single frequency channel like other protocols. However, unlike previous ones, access point only can initiate data transmission. Thus collisions are avoided. Moreover, the wake-up schedule of each sensor node is known to access points. The access point can also make adjustments to preamble transmission time. This knowhow is gained from the ACK packet received from the sensor nodes once data is sent correctly. WiseMAC is more energy efficient but it has limitations in terms of scalability. This is due to limitations with fixed star topology.

3.2.2 Berkeley MAC (B-MAC)

Berkley MAC is a variant of CSMA with preamble sampling. However, it has an improved form of preamble sampling where energy beyond the noise floor is taken into account. This kind of selective usage ensures that the time of receiver is not wasted and its energy is not consumed for any insignificant activity associated with the channel. Moreover, the interval of channel sampling is adjustable at the side of receiver when there is activity important is identified. When channel is sensed busy and the energy is said to be beyond noise floor, the receiver waits until either timeout occurs or data is received. CSMA is implemented at the transmitter prior to long preamble packets and data are sent. For improved reliability, ACK is used as B-MAC operation. In addition to these RTS-CTS is also useful in case of networks with high load in order to reduce the problem of collision.

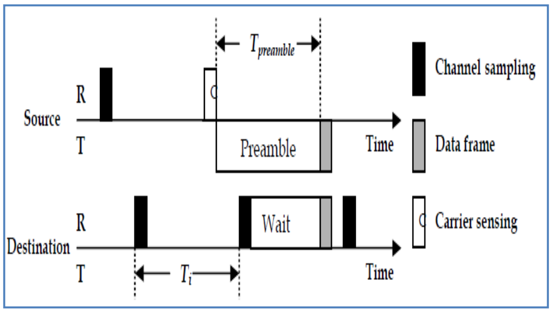

Figure 5: Shows basic operation in B-MAC

As presented in Figure 7, the whole wake up period of LPL structure is defined by B-MAC. There are two parts in the check interval namely sleep interval and listen interval. The operations of B-MAC in WSN have been analyzed and there was an analytical model developed. Different parameters are computed in order to optimize the applications and reduce power consumption. There are different variables known as sample rate, duty cycle, and check interval that are associated with an implication. These variables do have their impact on the performance of the protocol.

3.2.3 Speck MAC (SpeckMAC)

SpeckMAC is a variant of B-MAC where short packets are redundantly transmitted along with destination address embedded. Reduction of transmission energy is the idea behind this protocol. Towards this end, it has a measure for getting rid of or reduction of overhearing problem in the presence of heavy traffic conditions. The SpeckMAC has two variants. They are known as SpeckMAC-B and SpeckMAC-D where B refers to Back-off while D refers to Data. The former transmits wake-up frame along with target besides timing of transmission information. Any receiver employs selective sampling after wake up and address field is verified in the wake-up frame that has been received. When there is no matching address, it enters into sleep mode. If there is matching, the timer will be enabled in order to wake up later and gain data packet prior to going to sleep mode. The sender of the wake-up frame sends it till the data packet is transmitted.

3.2.4 X-MAC

X-MAC on the other hand uses a series of short preamble packets into which address of destinations are embedded. ACK packet is used here. However, it is not used after receipt of data packet. Instead it is used after sending first preamble packet. Thus it is possible to hit reception or active period of receiver. This way preamble packet transmission can be halted and data can be transmitted immediately. With respect to size of preamble packet, it is made short with redundant transmission till ACK packet is received by the sender. As in the previous mode, CSMA is carried out prior to sending preamble packets. Once the data packets are received by the receiver, it waits till other nodes get chance.

The X-MAC protocol is energy efficient and achieves low latency operations besides reducing energy consumption and burdens on transmission periods, idle listening and overhearing of neighbouring nodes. There is one concern which is related to mistakenly understood preamble data packet transmission. In such cases, it may lead to collisions.

Table 2: Summary of asynchronous duty cycles MAC protocols

MAC protocols	Target Applications	Key Design Principles	Strengths	Weaknesses
B-MAC	Monitoring events with different network conditions.	CSMA-based design. It is possible to adjust sleeping schedule. Can adapt to changing conditions of traffic. Supports adaptive preamble sampling. MAC is reconfigurable with a set of parameters. Interface is flexible and well defined.	Energy efficiency and throughput are high. MAC allows set of parameters that are reconfigurable. Dynamic to traffic conditions.	Long preamble may introduce additional latency. There is no solution for hidden terminal problem.
X-MAC	Monitoring events with dynamic traffic loads and multi-hop based applications.	Series of short preambles are transmitted with strobed preamble approach. For target receiver short preamble is used with address information embedded. Adaptive duty cycle approach is used to cater the needs of dynamic traffic loads.	Reduction of overhearing problem. Saves energy of transmitter and receiver by cutting preamble. It can adapt to dynamic traffic loads.	The hidden node problem is not yet resolved as CSMA is used.
WiseMAC	Applications that use low and medium data rates. Multi-hop based applications.	Wake up preamble length is minimized. Among neighbors sampling schedule is exchanged. For smaller wake up size, it exploits the knowledge with respect to sampling schedule of direct neighbors.	Synchronization overhead is removed by decoupling sender and receiver. Just-in-time preamble is achieved with sampling schedule exchange.	In case of non-target receivers, overhearing problem exists. Over multi-hop path end-to-end delay is observed.
SpeckMAC	Monitoring events with different network conditions.	Short packets are redundantly transmitted along with destination address embedded. Reduction of transmission energy.	Reduces of overhearing. Transmission energy is reduced.	Overhearing problem still occurs.

As shown in Table 2, the summary of various asynchronous duty cycles MAC protocols is presented. The protocols include WiseMAC, B-MAC, X-MAC and SpeckMAC.

IV. SUMMARY OF THE MAC PROTOCOLS

This section provides summary of various techniques related to MAC protocols, advantages and limitations of the protocols.

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Table 1: Summary of MAC protocols

REF	TECHNIQUES	ADVANTAGES	LIMITATIONS	SIMULATION TOOL
[1]	Radio duty cycling in a dynamic cyclic channel	Overcomes cyclical channel problems with new MAC protocol.	Multiple sources and wake up prediction are not yet considered.	Cooja simulation on Contiki OS
[2]	Evolution of MAC protocols	Duty cycles based MAC are explored.	Partially overlapped channels with MAC are yet to be explored.	Simulation tools not specified.
[3]	Adaptive SMAC protocol	Low duty cycle operation and Energy efficiency	Not specified.	NS2
[4]	A short preamble MAC protocol for duty cycled WSN	Energy efficiency, reduced per hop latency and flexible adaptation.	Reduction of listen time in duty cycled WSN is to be investigated.	Numerical simulation.
[5]	Contiki MAC radio duty cycling protocol	Power efficient wakeup mechanism.	Not specified.	Contiki simulation environment
[6]	Receiver initiated asynchronous duty cycle MAC protocol	Reduce occupation of wireless medium, improves PDR, power efficiency and throughput.	Not specified	NS2
[7]	Exploiting periodicity in body WSN	Energy efficiency, reduction of error rate, improvement in throughput.	Fine tuning is required to reduce computational overhead.	NS2
[8]	Mobility Aware Power Save Model (M-PSM)	Power efficiency and increased throughput.	Delay and handoff are yet to be investigated.	Trace based simulations
[9]	Temporal correlation in wireless channel	Increasedthrough put and energy efficiency	Not specified.	Simulation study
[10]	Technologies on intelligent tires	Energy harvesting	Battery less active system is to be explored.	Review of literature
[11]	Wake up radio for WSN.	Overcomes problems of overhearing and idle listening, energy efficiency, reduced latency and increased	Not specified but indicated that switching from duty cycled to wake up radio is required.	OMNET++

		PDR		
[12]	Opportunistic MAC protocol in WSN for wind turbines	Energy efficiency	Low power wakeup radio and outside support for track rotation of blade is yet o be explored.	Cooja in Contiki OS

As presented in Table 1, it is evident that different techniques are used for improving MAC protocol to meet duty cycled WSN. An important research gap found in [12] is that the MAC protocol created for wind turbine application is that it is yet to achieve lower power wakeup radio and need to have external support for track rotation of blades. It is important in the opportunistic, energy efficient MAC protocol for wireless communications in a duty-cycled or dynamic channel. There needs to be three-way rendezvous needed among sender node, receiver node and channel cycle. This is not supported by many existing duty-cycled MAC protocols. BladeMac [12] is able to provide this feature. It is a practical solution for wind turbine blade deployment over conventional WSN hardware. It is used for acquiring data related to power generation dynamics using wind turbines. BladeMac has its limitations. Alternative approaches can be explored using emerging technologies. Source nodes can be subjected to extremely low power wake-up radio system in order to respond to wake-up calls from sink instead of depending on RSS samples and idle listening. This can be overcome when source node is able to get required intelligence from outside the network stack.

V. CONCLUSION AND FUTURE WORK

MAC protocol is the sub layer of data link layer of OSI reference model. It plays crucial role in communication networks. In the traditional deployment of WSN, the MAC layer takes care of allowing multiple users to share a common channel. However, this kind of deployment is not suitable for duty cycled WSN which is required in many applications like wind energy system. In such network, the MAC has to determine rendezvous (a time and place where both sender and receiver's radio are on and communication can happen). This paper has focused on both kinds of MAC protocols in some detail. There are many insights related to simulation environments, MAC protocol functionalities and the deployment environments. In future we intend to propose a MAC protocol that is more suitable for wind turbines application where dynamic cyclical channel is used. Particularly the research gap explored in the previous section is an important direction for future work.

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