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Multi-Channel Mac Protocols in Wireless Sensor Networks: A Review

Vikash Kumar*
Student M. Tech, Computer Science,
Himachal Pradesh University, Shimla, India

Jawahar Thakur
Associate Professor, Computer Science
Himachal Pradesh University, Shimla, India

Abstract*— WSN is a rapidly emerging field with a lot of applications in real world scenario. With the advancement of software and the underlying hardware components i.e. the micro-electronic components, the sensor networks are proving to be applicable for a large number of subjects. A number of autonomous sensor nodes are deployed in difficult or possibly unreachable terrains to monitor the desired physical or chemical phenomenon. The communication process is controlled and managed by the MAC protocols. Due to the small size and the hardware constraints sensor networks usually face some problems regarding energy efficiency. To enhance the network lifetime and performance a lot of research and study has been conducted on MAC protocols. A relatively new and promising Multi-channel MAC platform provides better bandwidth utilization and enhanced network performance. As a result of the work done in the field of Multi-channel MAC protocols, a number of protocols are available which differ on the basis of challenges faced by them as well as their parameters. In this paper, a comprehensive and comparative study of a few Multi-channel MAC protocols is presented in accordance to their operating parameters.

***Keywords*— Wireless sensor networks, Medium Access Control, Multi-channel, energy efficiency, channel access.**

I. INTRODUCTION

Wireless sensor networks (WSNs) consists of a set of hundreds or potentially thousands of nodes, that are interconnected through a wireless medium to interact with the environment to monitor the physical and environmental conditions. Sensor networks are composed of sink node and a number of sensor nodes in the sensing field that work in a many -to –one fashion for the monitoring applications based on low rate data collection[1, 5]. The purpose is to collect and process the data from a target domain and transfer that information back to the sink. WSN is an emerging technology that's concerned with the sensing and controlling of physical parameters through small sensing and processing elements (nodes) that are deployed either inside or very close to the phenomenon. WSNs are expanding their applications in monitoring applications such as environmental/earth monitoring, natural disaster prevention, industrial monitoring, agriculture, passive localization and tracking, smart home monitoring, human health care, military & intelligence surveillance, targeting systems, etc.

Nodes in a sensor network are spatially distributed autonomous devices that co-operate among themselves through unattended, short-range communication to fulfil bigger tasks that single node couldn't. The nodes are self-organizing and constitutes a multi hop network that transmit the time series of sensed phenomenon to sink where computations are performed and data are fused.

A node in a sensor network constitutes of four main components:

a) Sensing devices (one or many): These are radio frequency modules that work on half duplex mode of communication for the purpose of data acquisition.
b) Transceiver: It's a low power transceiver or other wireless communication device for communication between the nodes in the sensing field. It can also have some moderate amount of memory.
c) Embedded processor: The data being collected by the sensor nodes from the sensing field is first processed locally before its delivery to the sink. For this purpose of local data processing the embedded processors are included in the composition.
d) Energy source: The energy is the major concern for the functioning and the lifetime of the sensor networks. Thus an efficient battery source is required for efficient working of WSN.

The strength of the sensor networks lies in its flexibility and scalability. Along with these strengths, WSNs also have some issues regarding energy efficiency and some resource constraints, as the nodes in the sensor networks are left unattended after their deployment in terrains where the energy replenishment is nearly impossible. These issues are more elevated because of a considerable amount of energy wastage during the sensing and communication. The major sources of energy waste are: Collision, Overhearing, Idle Listening, over emitting, Control Frames Overhead/ packet overload, and frequent switching. Hence the main objective of WSN is to maximize Node/Network lifetime, minimize communication while achieving the desired network operation. To achieve these objectives, and to ensure the efficient and successful operation of the network MAC protocols are employed. Media Access Control (MAC) layer [6] is the sub layer of data link layer for medium access control and management. The data link layer provides SNs with communication functions to share the wireless medium efficiently as well with essential error control tasks. Media Access Control and transmission scheduling is a key area of wireless sensor network research. MAC is a technique that creates the WSN infrastructure by establishing the communication link between the sensor nodes, avoids collisions from the interfering nodes, and hence helps to prolong the lifetime of the network. Mac protocols resolve the problem of co-ordination in time and channel domain by controlling the activity of nodes' radio transceivers directly and therefore making a strong impact on overall network performance and energy efficiency by providing the nodes with equal share of channel bandwidth. Single channel communication in WSN suffers throughput degradation in multi-hop environments because of collisions and unfair channel access, especially when the system is dense and traffic is high. To deal with these issues Multichannel MAC is the technology that provides maximum concurrency and hence provides parallel transmission over a number of frequency channels in a common spatial domain.

The rest of this paper is organized as follows: Section II describes the multi-channel communication and various multi-channel MAC protocols in sensor networks. Section III provides conclusion and future work for this review.

II. MULTI-CHANNEL COMMUNICATION IN WSNS

Multi channel MAC protocols [14] improve network performance of Wireless Sensor Networks (WSNs) via parallel transmissions. A multichannel MAC protocol enables hosts to dynamically negotiate channels so that multiple communications can take place in the same region simultaneously, each in different channel. Here the parallel data transmission is provided to handle busy traffic or provide multi-task support. It's helpful in the field of effective utilization of spectrum and integrating various networks in to an advanced global network.

The main challenges here are:

- How to allocate the channels? and,
- How to achieve the cross channel communication with energy efficiency and the cost factor?

Sensor nodes usually are equipped with a single transceiver utilizing a single channel. Therefore, WSNs cannot provide reliable and timely communication with high data rate requirements due to radio collisions and limited bandwidth. With improvement in device hardware, support for multi-channel communication is already in a advanced stage of implementation. Therefore, it is necessary to design multi-channel MAC protocols to take full advantage of parallel transmission to enhance throughput and performance of WSNs.

I. MC-LMAC: Multi-channel lightweight MAC

MC-LMAC [3, 12] is a TDMA based protocol which is designed to exhibits significant bandwidth utilization and high throughput while ensuring an energy-efficient operation. The protocol provides contention-free parallel transmissions by coordinating transmissions over multiple frequency channels. It exhibits time scheduled communication that eases the coordination of nodes, switching dynamically between the channels and thus, the communication proving to be robust during high peak loads. Time is slotted and the individual nodes are assigned the control over the particular channel for their transmission. The time slots and the channel assignment are done in a fully distributed manner so as to provide non-conflicting transmissions. A time slot consists of a control period during which all the nodes switch their interfaces to a common channel and a data transmission period during which the data transmission over the assigned channels takes place.

The protocol is based on single-channel LMAC [10], which is an energy-efficient medium access protocol designed for WSNs. The LMAC protocol enables the scheduled access for the nodes to the wireless medium in which each node periodically uses a timeslot for transmission. A few important aspects of LMAC [12] are:

- Self-configuration: LMAC can operate in a fully-distributed ad hoc manner and does not require a centralized scheduler.
- Adaptability to changes: LMAC can adapt the communication schedule according to network dynamics.
- Energy efficiency: Through timeslot scheduling, energy wasting can be avoided by taking advantage of collision-free medium access.

MC-LMAC addresses the challenges of multi-channel communication such as network partitioning, channel switching, broadcast support and new nodes joining a network efficiently and solves these problems with its synchronized TDMA-based communication and with a channel reserved for broadcasts.

II. MMSN: Multi-channel MAC protocol for sensor networks

MMSN [3, 4] is actually a contention based multi-channel MAC protocol for WSNs. The protocol provides CSMA based medium access where time is divided in slots, with each slot consisting of: a broadcast period in which a node strive to gain access of the same broadcast frequency and, a transmission period in which a node compete for shared uncast frequencies to broadcast a message. The protocol is based on snooping mechanism where the channels are assigned to the receivers that help in maximizing parallel transmission among neighbouring space. At the beginning of each timeslot nodes contend for the medium before they can transmit. This is done through listening to the channels both: on its own frequency and on the destination's frequency, and accordingly switching between the channels. Each node's behaviour differs depending on whether it has a packet to transmit or not, as well as whether it has a unicast packet or a broadcast packet to transmit. First, the check is made for the broadcast frequency of each node to receive or transmit a broadcast packet. In case there is no broadcast packet to transmit or receive, unicast packet transmission and reception are considered. If node has no packet to transmit, it's must be ready for receiving

The operating of MMSN protocol includes of two activities: frequency assignment to assign frequencies to the nodes from the available frequencies such communication conflicts or the potential collisions may well be minimized and providing media access to the nodes. A special broadcast channel is used for broadcast traffic at the beginning of each timeslot. The MMSN protocol provides low latency and high throughput at lighter load but as the traffic load rises, along with it the contentions and collisions also rise. This protocol goes against the energy efficiency because of due to frequent channel changing. MMSN successfully resolves missing terminal problem by alternately listening both channels, its and receivers channel.

III. Y-MAC

Y-MAC [15] is a TDMA-based, hybrid multi-channel MAC protocol that employs a light-weight channel hopping mechanism. It is an energy-efficient multi-channel MAC protocol (with contention in each slot) for dense WSNs where the time slots are assigned to nodes for receiving instead of transmitting. Time is divided in to frames consisting of a broadcast period and a unicast period. Potential senders for the same receiver compete to access the medium at the beginning of each time slot. The slots are assigned in accordance to a slot allocation vector, which contains occupied time slots within its own one-hop vicinity as well as itself. The information about the occupied time slots in their two-hop vicinity is gathered by the nodes from this vector by OR-ing the vectors. Now in accordance to the gained information time slots are randomly selected by the nodes from the available slots. Here the slot must be long enough to receive one Message. It avoids redundant channel assignment by not allocating fixed channels to the nodes. Initially, messages are exchanged on the base channel**.** On occurrence of a traffic burst, a receiver and potential senders hop to one of the other available channels in accordance to the hopping sequence. This is done as long as there are potential senders for that node and in the meantime the remaining nodes continue to exchange messages according to slot schedules. All nodes are awake at the beginning of the broadcast period. If there are no incoming broadcast messages, each node turns off its radio until its own receive time slot to save energy. For unicast period, nodes have assigned time slot, for exclusive receiving.

IV. ARM: Asynchronous receiver-initiated multichannel MAC

ARM [7]: an asynchronous receiver-initiated multichannel MAC protocol, is a duty cycle based protocol that employs a dedicated control channel approach to control the saturation in control channel and other problems like triple hidden terminal and low broadcast reliability problems in asynchronous multi-channel WSNs. The channel saturation and triple hidden terminal problems are solved through the use of probability-based random channel selection and the receiver-initiated transmission scheme. On the other hand, a receiver-adjusted broadcast scheme guarantee the broadcast reliability of the broadcast-intensive applications.

The protocol is based on duty-cycled WSN and hence conserves energy by keeping nodes in the sleeping state. As a receiver wakes up, it broadcasts an announcement message on the common control channel which includes the channel number that the receiver will switch its interface on. On receiving this announcement message, the sender also switches its radio to the announced channel. After a random delay, the sender sends an RTS message which is answered by a CTS message by the receiver if the RTS is received successfully. After the sender reserves the medium with the CTS, data transmission starts. When the transmission is complete, the pair switches back to control channel and enter the sleeping period. A separate broadcast channel is used to support the broadcast messages. The protocol ensures that every node, i.e. potential receivers, switches to the broadcast channel for periodic intervals. When a sender has a broadcast message it transmits the message for a period which is long enough for the potential receivers to switch their interface on the broadcast channel. The protocol is based on duty-cycling so as to conserve energy and to address the common control channel issues and multi-channel hidden terminal problems but on the other hand and this protocol cannot always guarantee a collision-free transmission on the selected channels as the channels are selected randomly and probabilistically by the nodes and they do not preserve any information about the free or used channels for usage.

V. MUCHMAC: Multi-channel MAC

MuChMAC [3, 8, 9], is a dynamic multi-channel MAC protocol based on the frequency-hopping approach. It provides a solution for low-power wireless sensor networks by employing a distributed algorithm to scale MuChMAC's duty cycle based on the amount of traffic passing through a node. It considerably improves the packet delivery performance under high traffic loads, while it preserves the low overhead of the network under low traffic loads. To support the broadcast messages, special broadcast slots are used. Some of the important aspects of MuChMAC's design are:

- Low Power: MuChMAC keeps nodes in a low duty cycle to conserve energy and hence extends battery lifetime. Nodes wake up during only a small portion of a slot and sleep in the rest to support the low-power operation of the network.
- Frequency Agility: MuChMAC employs channel hopping approach to avoid collisions and reduce the effect of external interference. Especially in dense networks, channel selection may cause multiple nodes to select the same channel during the same slot. To prevent this, slots are divided into sub slots.
- General Purpose: MuChMAC can be used under a wide range of traffic loads, ranging from one packet per hour to one packet every few seconds. Both unicast and broadcast traffic are explicitly supported. To accomplish a low overhead even when there is little traffic, the algorithms used in MuChMAC are entirely distributed.

MuChMAC takes advantage of channel hopping and achieves this without the requirement of tight synchronization.

VI. TMCP: Tree-Based Multi-Channel Protocol

TMCP [2] is Tree-Based Multi-Channel Protocol for data collection applications. The main task here is to partition the network into multiple vertex-disjoint sub-trees (all rooted at the base station), while minimizing the intra-tree interference by assigning different channels to the nodes residing on different tree branches starting from the top to the bottom of the tree. The aim of partitioning is to scale back potential interference in so far as attainable. After the partition, different channels are allocated to each sub-tree one by one, from top to bottom of the tree by following a greedy approach. Hence, the tree construction and channel assignment operations are combined. The nodes broadcast their channel information to their neighbours. For a new node to be added to the tree, the sub-tree where the node brings the least interference is selected to minimize the intra-channel interference on the same branch. When a node needs to send info to the base station, it simply uploads packets on to the sub-tree it belongs. The protocol reduces channel switching and communication among nodes with different channels and hence avoids the complex coordination methods.

The advantage of TMCP [13] is that it does not require channel switching and it also supports convergecast traffic. However, it is difficult to have successful broadcasts due to the partitions, and contention inside the branches is not resolved since the nodes communicate on the same channel.

Table I: Comparison of Multi-Channel MAC Protocols

Parameters / Protocols	**Topology**	**Assignment method**	**Implement-ation**	**Broadcast support**	**Control ch.**	**Synchro-nization**	**Medium access**	**Data transfer (channel selection)**	**Channel switching**	**Objective**
MC-LMAC [12]	Tree	Semi-dynamic	Distributed	Yes	No	Required	LMAC	Sender	Once per timeslot	Improve the achievable throughput of WSNs
MMSN [4]	Flat	Semi-dynamic	Distributed	Yes	No	Required	Slotted CSMA	Receiver	Multiple times per timeslot	Increase parallel transmission
Y-MAC [15]	Non-clustered	Dynamic	Distributed	Yes	No	Required	TDMA	Receiver	Once per timeslot	Handling bursty traffic, energy efficiency
ARM [7]	Flat	Semi-dynamic	Distributed	Yes	Yes	No	CSMA/CA	Receiver	-	Tackle control channel saturation, low broadcast reliability and triple hidden terminal
MUCHMAC [8, 9]	Flat	Dynamic	Distributed	Yes	No	Required	TDMA, X-MAC	pseudo-random	-	Improve bandwidth, low power operations
TMCP [2]	Tree	Fixed	Centralised	Inside branches of the tree	No	No	IEEE 802.15.4/ ZigBee	Sub-tree	Reduced	Efficient data collection
TFMAC [16]	Flat	Semi-dynamic	Distributed	Yes	No	Required	Slotted	Receiver	Once per timeslot	Efficient data collection

*VII. **TFMAC: Time- Frequency MAC***

TFMAC [16]: abbreviated from Time- Frequency MAC, is a TDMA-based multi-channel MAC protocol designed for wireless sensor networks in which each sensor node is equipped with a single half-duplex transceiver with multiple-frequency support. It is a hybrid MAC protocol that incorporates multiple channels into a traditional TDMA scheme allowing different sensor nodes in a neighbourhood to transmit on different channels simultaneously. TFMAC allows concurrent transmissions to take place within the same two-hop neighbourhood during the same time slot. It exploits the existence of multiple channels and the ability of transceivers to switch between them quickly to increase network throughput. TFMAC divides time into a fixed number of time slots and allows each node to use different frequencies within different time slots to send data packets to its neighbours. Slot assignment is accomplished in a distributed way, through exchange of a limited number of controls messages during the contention slot at the beginning of each time frame. And hence it provides conflict-free communication for data packets. Slots are assigned by exchanging control messages during the contention slot at the beginning of each time frame. TFMAC consists of two phases: frequency assignment and media access. The protocol employs a simple frequency assignment scheme: each node randomly selects a number of frequencies as its receiving frequency and then broadcasts the frequency decisions to its neighbours. After the frequency exchange, nodes set up timetables such that transmissions from the nodes are conflict free in time and frequency domains. In the media access phase nodes access the medium in a TDMA-fashion. The slot and channel selection mechanism incorporated in the protocol is rather complex since nodes need to follow transmission, reception and idle slots separately.

III. CONCLUSION AND FUTURE WORK

In the emerging field of sensor networks the number of MAC protocols is being expanding and because of the application specific nature of the protocols, no one can be accepted as a standard. Hence, the comparison is usually done on the basis of implementation parameters apart from the challenges they face. An overview of the media access control mechanisms employed in current multi-channel MAC protocols specifically proposed for WSNs is been presented in this paper. The main aim of design of MAC protocols is to reduce energy consumption while increasing performance. For this very reason multiple channels are used to alleviate the effects of interference factor and improve the capacity. The effectiveness of multi-channel MAC protocols mainly depends on the channel assignment strategy, which has to guarantee both fairness and low signalling overhead. For a comparative study a set of protocols covering the widest possible breadth were selected. The parameters and a comparative analysis are shown in table I. Here, Implementation depicts the platform for the channel assignment and the network functionality. The implementation of channel assignment can be centralized or distributed. Control channel is used for exchanging control messages or the channel usage information such as the channel number that the receiver will switch its interface on. Assignment method depicts how radios are assigned the channels. It can be fixed assignment, semi-dynamic assignment or dynamic assignment. Synchronization reports if the protocol requires any external time synchronization or not. Medium access depicts the schedule or the mechanism of how the protocol accesses the medium. Broadcast support outlines whether the protocol supports broadcast or not. For this, protocols usually use a broadcast channel. Topology is the network architecture. It can be Peer to Peer (also called Point to Point), Star, Tree or Mesh. Data transfer channel refers to channel where sender and receiver have to switch for data transmission. Channel switching column shows the number of frequency switching the protocol needs to do in each step. Apart from the energy efficiency which is the primary concern of multi-channel protocols, the channel access mechanisms require further work such as experimentation of channel interference, assignment overlapping channels and contention mechanism. Also with the emergence of multi-channel protocols some research is needed to be done on performances of hybrid multi-channel MAC protocols.

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