Multi-Channel Media Access Control for Wireless Sensor Networks: a Survey

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Abstract – **This paper deals with multi-channel Media Access Control (MAC) protocols for Wireless Sensor Networks (WSNs). We first give an overview of multi-channel communication in WSNs and propose the classification of existing multi-channel MAC protocols for WSNs. Then, we describe briefly three representative protocols by stating their essential behavior and emphasizing their strengths and weaknesses.**

Keywords – **Wireless sensor networks, Multi-channel medium access control, Energy efficiency.**

I. INTRODUCTION

A wireless sensor network (WSN) consists of a number of autonomous and inexpensive sensor nodes. Each of them is composed of sensors, a low-power radio transceiver, small amount of memory and processing capability as well as limited battery power supply. The WSN should consist of hundreds or thousands of such tiny devices deployed in ad-hoc manner, which are able to sense the environment, compute simple task and communicate with each other in order to achieve common objective, like environmental monitoring, target tracking, detecting hazardous chemicals and forest fires, monitoring seismic activity, military surveillance [1]. The primary objective in WSN design is maximizing node/network lifetime, leaving the other performance metrics as secondary objectives. Since the communication of sensor nodes is more energy consuming than their computation, it is a primary concern to minimize communication while achieving the desired network operation.

Media Access Control (MAC) is a key component to ensure the successful operation of WSNs and it has obtained intensive research attention [2]. A MAC protocol decides when competing nodes could access the shared medium to transmit their data and tries to ensure that no collisions occur. MAC protocol controls the activity of nodes' radio transceiver directly, and therefore makes a strong impact to the overall network performance and energy efficiency.

MAC protocols for WSN can be categorized as follows [3]: scheduled protocols (which are optimized for periodical traffic, like with multimedia), protocols with common active period (which are optimized for medium traffic, typically with industrial applications), preamble sampling protocols (suitable for infrequent traffic, typically for measurement applications)

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and hybrid protocols (which combine advantages of existing protocols).

Most of the MAC protocols proposed specifically for WSNs assume the use of simple, low-cost transceivers that can operate on a single channel (frequency), only. But, with higher density networks can easily deteriorate communicational capacity of a single channel, and decrease network performances, due to increasing of collisions and conflicts. In the same time, the current commercial, low-power transceivers, such as CC1100 [4], already provide the basic functions required to support multiple channels. Such transceiver cannot transmit and receive at the same time, but it can switch the operating frequency dynamically. Hence, many novel studies propose usage of multiple orthogonal channels for communication in WSN. Availability of multiple channels adds one more degree of freedom to wireless communications that can be exploited to increase the spatial reuse by providing more simultaneous transmissions than is possible in single-channel WSNs. Thus, network throughput can potentially be increased. Intermediate benefits of multichannel can be: throughput increasing, inter-network interference minimization and external interference avoidance.

In this paper, we give a survey of the multi-channel MAC protocols for WSN. Section II emphasizes the distinct features of multi-channel communication in WSNs. Section III first introduces classification of existing multi-channel MAC protocols based on media access mechanism employed, and then presents key multi-channel MAC protocols proposed for WSNs listing their advantages and disadvantages.

II. MULTI-CHANNEL COMMUNICATION IN WSN

Multi-channel communication improves throughput by allowing simultaneous transmissions. But, for successful transmission, both nodes should be set on the same channel in the same time. MAC level protocols should resolves problem of coordination in time and channel domain. Designing of an efficient multi-channel MAC protocol is complicated, since, besides standard single-channel MAC related problems, new multi-channel-related problems occur.

Multi-channel hidden terminal problem. Besides standard single-channel hidden terminal problem, multi-channel communication have additional problem of not hearing announcement at one channel, when node is occupied at another channel [5].

Multi-channel missing terminal problem. Occurs when packet on the control channel misses its destination, occupied on another channel [6].

Broadcast support problem. Due to the diffused character of the wireless medium, broadcast is easily realized in single-channel networks. Since with the multi-channel communication different nodes have different receiving channels, broadcast message must be emitted at every channel.

Channel allocation problem. Packet transfer with multi-channel communication is feasible only if both, transmitter and receiver operate at the same channel. Therefore, multi-channel MAC protocol should have efficient channel allocation strategy. Efficient channel allocation strategy should evenly distribute channels among nodes and has capability of overcoming hidden terminal problem.

Channel switching time problem. Radio transceiver needs certain amount of time on channel switching (e.g. 300 µs with CC2420 [7]). During this time, receiving and sending are unable, so the frequent channel switching leads to increasing of delay and decreasing of throughput. This is especially critical with WSNs, where the time for transmitting one message (which is relatively small) is nearly as short as the time for channel switching. Apart from loss of time, frequent channel switching implies additional energy loss.

Number of channels problem. Although existing radio transceivers for WSNs have ability of setting working frequency to high number of channels, number of available orthogonal channels is round to 10. For example, radio transceiver CC2420 [7] offers 16 different working channels in 2.4 GHz frequent range, they cannot be used all, due to channel overlapping, which could lead to interference.

Synchronization. In case of dynamical channel allocation, when nodes can switch channel), strict switching channel coordination is needed in order provide presence of both, transmitter and receiver, on the same channel. The same problem does not exist with multi-channel MAC protocol with fixed channel allocation.

Partitioning. Neighboring nodes cannot communicate, if they are on different channels. This phenomenon is called network partitioning. Therefore, it is essential to establish which nodes need to communicate, in order to give them the same channel. Channel allocation should be repeated periodically, in order to adapt to network changes.

Joining to the network. If newly joint node randomly chooses channel, it could disrupt channel organization in its neighborhood. One possible solution could be that node first listens all channels for the certain amount of time, in order to choose free channel for emitting.

III. Multi-Channel MACs for WSNs

In this section, we limit our discussion to synchronous, i.e. frame-based multi-channel MAC protocols, which use coordinated scheduling to reduce idle listening and save energy. These protocols differ in the media access mechanism used for collision avoidance, and can be classified into three categories: scheduled protocols [8][9], contention protocols [10], and hybrid protocols [11].

Scheduled multi-channel protocols. In this scheme, each node is assigned a time slot in TDMA frame for data transmission, unique in its 2-hop neighborhood. This guarantees collision-free medium access, and protocol does not waist energy and bandwidth on competition and collisions. However, since the nodes must be awake at the beginning of the each neighbor's slot in order to check for possible transmissions, scheduled multi-channel MAC protocols have increased energy consumption in absence of traffic. A common difficulty with scheduled MAC protocols are the schedule adaptation to topology changes where these changes are caused by insertion of new nodes. The number of slots per frame depends on network density; the higher number of slots induces higher delay. Introducing multiple channels lowers number of slots per frame, and thereby reduces delay.

Contention based multi-channel MAC protocols. Contention based multi-channel MAC protocols do not impose a predetermined transmission schedule nor the frame is divided into time slots. Instead, contention procedure is conducted at the beginning of each frame, beforehand every transmission, in order to avoid collisions. Contention based MAC protocols allows small delay and high throughput in cases of low traffic. However, they have a problem with high traffic, when throughput deteriorates and energy consumption increases due to intensive contention of competing transmitters and frequent collisions of data packets. Also, additional collision avoidance or collision detection methods should be employed to handle the missing and hidden terminals problem.

Hybrid protocols. These protocols combine principles from previous two groups. The frame is divided into time slots, but slots are assigned to receivers instead of transmitters. In the absence of traffic, hybrid protocols are more energy efficient then scheduled protocols, since each node need to be awaken to receive data only once per frame. Although hybrid protocols require contention of the potential transmitters at the beginning of each slot, contention mechanism is simpler and wastes less energy than with contention based protocols since there is always only one receiver. Additionally, the throughput is increased at high traffic, since the contention is distributed over multiple time slots.

In what follows, three representative multi-channel MAC protocols defined for WSNs are described briefly by stating their essential behavior. Moreover, the advantages and disadvantages of these protocols are presented.

A. TFMAC

TFMAC is a scheduled multi-channel MAC protocol for WSNs with self-configuration capabilities and autonomy of operation [9]. The protocol operation is divided into two main phases: *initialization phase*, where sensor nodes first discover their neighbours, and then cooperatively establish collision-free multi-channel TDMA schedule, and *active phase*, when regular data communication is taking place.

Protocol assumes that all nodes are synchronized during the active period. In TFMAC, time is partitioned in consecutive frames of fixed duration and each frame consists of a contention access period, followed by a contention-free period (Fig. 1). The contention access period, referred as *control slot*, is used to exchange control messages needed to maintain the protocol. All nodes must monitor the default frequency

channel during this time period. The communication during the control slot is contention-based and uses the same scheme as the one used in 802.11 DCF [8]. The contention-free period, on the other hand, is used to transfer data between nodes. Each contention-free period is further divided into N_t equal sized *time slots* numbered from 0 to N_t-1. The duration of a time slot is long enough to accommodate transmission of one or more data packets. Transmissions in time slots are scheduled to avoid collisions.
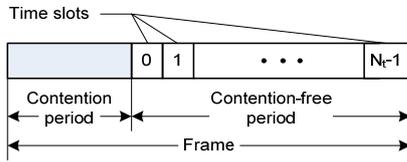

Fig. 1. TFMAC frame organization.

The timetable is the main local data structure that needs to be maintained at each node to keep current time slot usage information. For each time slot, the timetable contains an entry: (i, t, f), where i is the slot number, t is a slot type and f is the index of frequency used in that slot. Allowable slot types are: T, for transmission slot, R, for reception slots, and I, for idle slots.

In a network setup with N_F available frequencies, each node is assigned N_F transmission slots, and each transmission slot is assigned a different channel that is used for data transmissions. On the other hand, each node is assigned a single receiving channel that it uses to receive data packets during its reception slots. Every node has one reception slot for each neighbor.

A TFMAC slot schedule is correct if for any given node n_i the following two conditions are satisfied:

• The transmission slot when n_i transmits on channel frequency f_j overlaps with reception slots of all its neighbors with assigned receiving frequency f_j.

• During the transmission slot when n_i transmits on channel frequency f_j, n_i is the only transmitter on frequency f_j in its two-hop neighborhood.

The first condition is necessary to provide a bidirectional data link between any two neighbouring nodes, while the second one ensures collision-free communication.

B. MMSN

MMSN is a contention based multi-channel MAC protocol for WSNs [10]. Media access is based on CSMA with time divided in time slots. Each slot consists of a broadcast contention period (T_{bc}) and a transmission period (T_{tran}), as shown in Fig. 2. Each node has assigned receiving frequency. With the assigned frequencies, nodes cooperate in media access to maximize parallel transmission among neighboring space. To provide efficient broadcast during the T_{bc} period, nodes compete for the same broadcast frequency f_0 and during the T_{tran} period, nodes compete for shared unicast frequencies, or transmit broadcast message. The T_{tran} period also provides enough time to transmit or receive a broadcast or unicast data packet.

Each node's behavior differs depending on whether it has one packet to transmit or not, as well as whether it has a unicast packet or a broadcast packet to transmit. Each node first checks the broadcast frequency for receiving or transmitting a broadcast packet. If there is no broadcast packet to transmit or receive, unicast packet transmission and reception are considered.
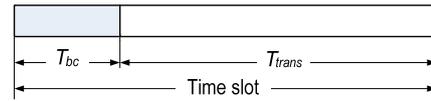

Fig. 2 MMSN time slot organization.

If node has no packet to transmit, it's must be ready for receiving, so, after the T_{bc} period, if there is no broadcast ongoing, node switches to snoop on frequency f_{self}, which is the frequency assigned to it for unicast packet reception. If a signal is sensed in frequency f_{self}, it receives the packet during the rest of the time slot, otherwise waits until the rest of the T_{tran} period is no long enough for the contention and message delivery and it turns off the radio for the rest of the T_{tran}.

If node has a unicast packet to transmit, and there is no broadcasting, the node takes a random backoff during which the node snoops on two frequencies. On one hand, it snoops on frequency f_{self}, which is assigned to it for data reception, to get prepared for a possibly incoming unicast packet. On the other hand, it also snoops on frequency f_{dest}, which is assigned to the destination node of its unicast packet for data reception. If frequency f_{dest} is sensed busy, the destination node is receiving unicast packet and the node chooses not to transmit the unicast packet in the current time slot to avoid collisions and switches to f_{self}. If the node senses any signal on frequency f_{self}, it gets to know that it itself is the destination of an incoming unicast packet, so it cancels ongoing sensing and receives the data packet. If node does not sense any signal on both frequency f_{self} and f_{dest} during the backoff time period, it sends out a unicast packet.

The advantage of the MMSN protocol is smaller latency and higher throughput, but only with lower traffic. With heavier traffic the number of collisions and contentions increases. MMSN successfully resolves missing terminal problem by alternately listening both channels, its and receivers channel. However, the protocol has increased energy consumption due to frequent channel changing, especially during contention for sending unicast message.

C. Y-MAC

Y-MAC is a hybrid multi-channel MAC protocol [11]. It is a TDMA-based MAC protocols with contention in each slot, since time slots are assigned to nodes for receiving, and not transmitting. Potential transmitters must content for transmission at the beginning of the each slot.

Time is divided into fixed-length frames, and each frame consists of a broadcast period and a unicast period (Fig. 3). 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.
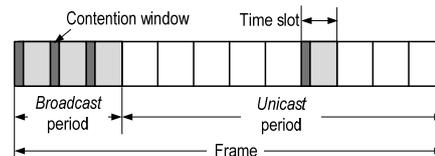

Fig. 3. Y-MAC frame architecture.

For unicast period, nodes have assigned time slot, for exclusive receiving. Contention between potential senders is resolved in the contention window. The node wishing to send a packet sets a random backoff value within the contention window. Then the node wakes up and checks the medium for a certain amount of time. If the channel is clear, a preamble is transmitted until the end of the contention window to suppress competing transmissions. The receiver wakes up at the end of the contention window to receive the data part of the message.
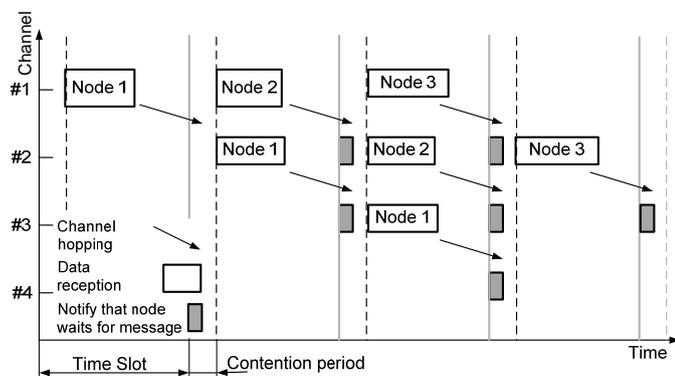

Fig. 4. A light-weight channel hopping mechanism.

Y-MAC proposes a light-weight channel hopping mechanism. It avoids redundant channel assignment by not allocating fixed channels to the nodes. Initially, messages are exchanged on the base channel. When a traffic burst occurs, a receiver and potential senders hop to one of the other available channels, according 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.

The advantage of the Y-MAC protocol is the introducing new channels only when it's necessary, with increased traffic, which minimizes channel. This scheme implicitly assigns N time slots (where N is number of available channels) to each node, which are used in case of necessity. The deficiency of this protocol is in contention mechanism at the beginning of the each slot, which does not eliminate collisions in case when potential senders do not hear each other. Also, the existence of additional contention periods lowers throughput and proposed contention mechanism increases energy lost. Another problem may occur in the base station neighborhood, where the traffic is increased, since the contention based protocols have problems with higher rate collisions. Finally, the problem may occur with node which has assigned the last slot in frame, which can lose part of the broadcast period due to hoping to other channel.

IV. CONCLUSION

In this paper we presented the overview of the media access control mechanisms employed in current multi-channel MAC protocols specifically proposed for WSNs. The use of multiple channels can certainly increase MAC protocol performance with low energy consumption. However, the design of a multi-channel MAC protocol depends on requirements of the actual application, regarding energy efficiency, throughput and delay, since no specific medium access scheme provides best performances over all traffic condition and network densities. We identified the hybrid protocols as the most promising approach for finding a tradeoff between high throughput of the scheduled protocols at high traffic and low energy consumption of the contention protocols at low traffic.

Future work directions include studying the impact of contention mechanism tradeoffs, such as those associated with contention window size as well as contention algorithm itself, on performances of hybrid multi-channel MAC protocols.

REFERENCES

[1] F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey", *Computer Networks*, vol. 38, no. 3, pp. 393–422, 2002.

[2] I. Demirkol, C. Ersoy, F. Alagoz, "Mac protocols for wireless sensor networks: a survey", *IEEE Communications Magazine* vol. 44, no. 4, pp.115–121, 2006.

[3] Abdelmalik Bachir at. al., "MAC Essentials for Wireless Sensor Networks", Accepted, *IEEE Communications Surveys and Tutorials*, vol. 12, no. 2, pp. 222-248, 2010.

[4] "CC1100 Low-Power Sub- 1 GHz RF Transceiver", http://www.ti.com

[5] J. So and N. Vaidya, "Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver" In *Proc. ACM MobiHoc*, pp. 222-233, Tokyo, Japan, 2004.

[6] J. Shi, T. Salonidis, and E. Knightly, "Starvation Mitigation through Multi-Channel Coordination in CSMA Multi-Hop Wireless Networks," In *Proc. ACM MobiHoc*, pp. 214-225, 2006.

[7] H. W. So, G. Nguyen, J. Walrand, "Practical Synchronization Techniques for Multi-Channel MAC", In *Proc. ACM MobiCom* `06, pp. 134-145, 2006.

[8] S. Dulman, O. Incel and P. Jansen "Multi-channel Support for Dense Wireless Sensor Networking", In Proc. of *EuroSSC*, pp. 1-14, 2006.

[9] M. Jovanovic and G. Djordjevic, "TFMAC: Multi-channel MAC Protocol for Wireless Sensor Networks", *TELSIKS'07*, *Conference Proceedings*, pp. 23-26, Nis, Serbia, 2007.

[10] G. Zhou, C. Huang, T. Yan, T. He, J. Stankovic and T.Abdelzaher, "MMSN: Multi-Frequency Media Access Control for Wireless Sensor Networks", In *Proc. Of IEEE Infocom*, pp. 1-13, 2006.

[11] Y. Kim, H. Shin, and H. Cha, "Y-MAC: An energy-efficient multi-channel mac protocol for dense wireless sensor networks" In Proc. of *IPSN '08*, pp. 53–63, 2008.