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Overview on Multi-Channel Communications in Wireless Sensor Networks

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Abstract

In this paper, we focus on multi-channel MAC protocols specifically designed for Wireless Sensor Networks (WSNs). The use of multiple channels helps overcome interferences and thus enhance the overall network performance. In order to establish channel and slot allocation to enable simultaneous transmissions, many protocols have been proposed in the literature. Some of them are based on a TDMA approach which offers a more deterministic behavior but requires a strict synchronization, while others are based on CSMA/CA which is an asynchronous medium access algorithm that suffers from collisions due to its probabilistic behavior. Different classifications have been proposed in previous survey papers depending on the periodicity of channel switching, on whether they are centralized or distributed, synchronized or asynchronous, etc. In this paper, we present a survey of the different techniques used in WSNs and that are applicable on the IEEE 802.15.4 standard. We detail some of the most popular protocols and discuss their advantages and weaknesses. We conclude the paper with an open discussion concerning future research directions.

Keywords: Wireless Sensor Networks (WSN), Medium Access Control (MAC), Multi-Channel, IEEE 802.15.4, synchronization.

1. Introduction

Wireless sensor networks (WSNs) [1] are an emerging technology that has been a growing success in the scientific and industrial communities. This technology was at first considered for low rate applications but has gained popularity and is now being considered for more demanding applications where the data rate is no longer low. This technology has a wide range of applications including environmental monitoring, security of property, smart buildings, medical care, industrial and military applications. Fig. 1 describes a typical WSN architecture. They consist of distributed autonomous sensor nodes that monitor physical or environmental conditions. These nodes are powered by small replaceable batteries and thus need to work in an energy efficient way while collecting data, processing it, and transmitting it to a certain concentration point called the sink. Hence, network protocols that are proposed for WSNs are energy efficient in order to better suit the application network lifetime constraint. For example, MAC protocols try to use the transceiver efficiently by avoiding collisions, idle listening, unnecessary transmissions, etc. [2].

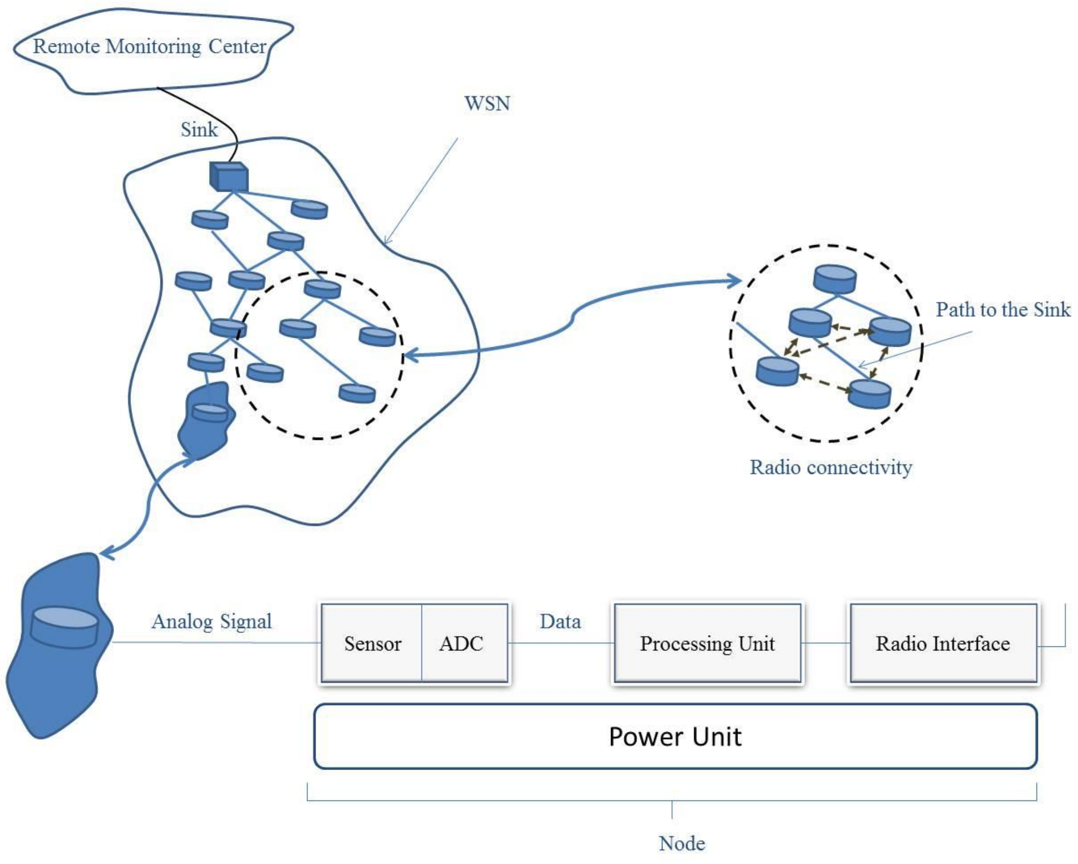

Figure 1. Description of a typical WSN Architecture.

All IEEE 802.15.4 [3] [4] compliant platforms provide a radio chip capable of switching its communication channel, and therefore is not restricted to a single channel operation. In a multi-hop topology, each packet must be transmitted several times in order to reach the final destination. This overloads the radio channel and induces interferences, and a risk of collision due to the hidden terminal problem [5]. This phenomenon results in data packet losses that lead to degradation of performance and inefficient bandwidth use. Many researchers have investigated the use of multi-channel in order to mitigate the consequences of interference. In cases where multiple channels are used, multiple nodes can transmit data through different channels simultaneously which increase throughput, provides robustness against interference and increase the capacity of wireless sensors networks. Fig. 2 shows an example of single channel use and how collisions occur at the receivers when multiple nodes transmit simultaneously. Fig. 3, on the other hand, shows how the use of multiple channels allows simultaneous collision-free transmissions for the same example.

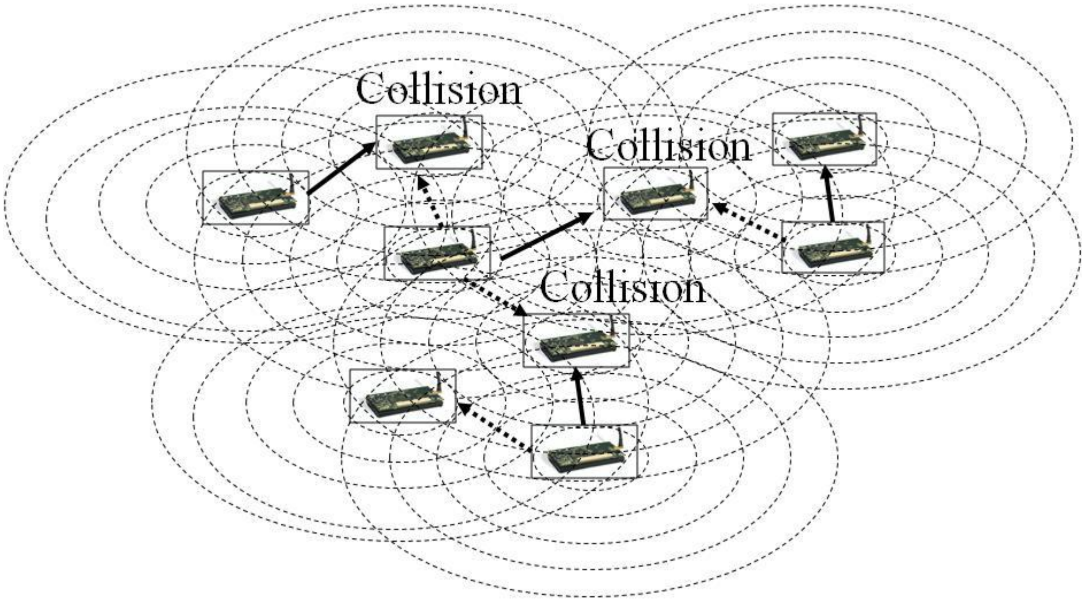

Figure 2. Using a single channel increases the probability of collision and interference.

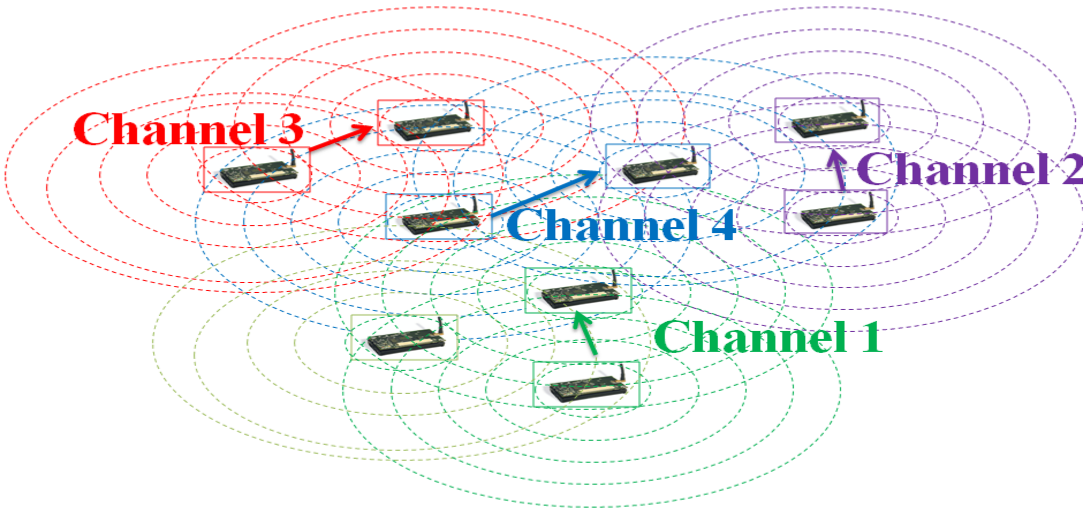

Figure 3. Using multiple channels decreases the probability of collision and interference.

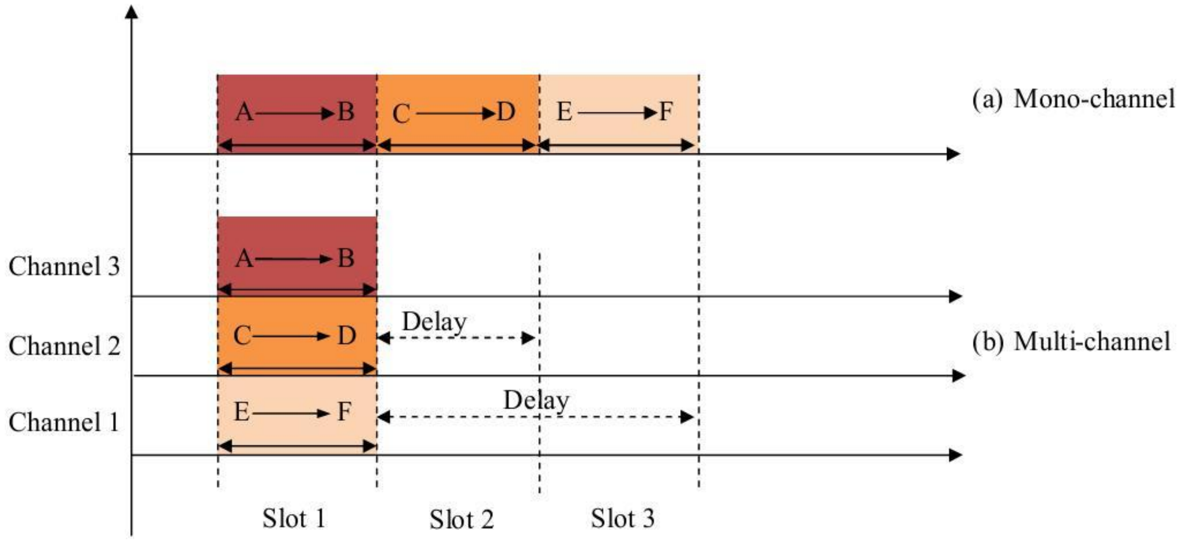

Figure 4. Comparison between a Mono-Channel scheme and a Multi-Channel scheme.

Fig. 4 represents a comparison between the use of mono-channel and multi-channel schemes. In the case of a mono-channel scheme the three transmissions are consecutive, while in the case of a multi-channel scheme, where three channels (1, 2 and 3) are available, the three transmissions can occur simultaneously, which enhances the bandwidth and reduces delays.

In this paper, we will only study existing multi-channel protocols that are proposed for WSNs and compliant with the IEEE 802.15.4 standard. In what follows, we will give a brief description of the different classifications of these protocols. In part 3, we describe the IEEE 802.15.4 standard on which we based our physical layer assumptions. In part 4, we go through the most popular multi-channel MAC protocols by highlighting their main contribution and discussing their weaknesses, we then summarize these protocols in a table. In part 5, we conclude the paper with an open discussion about the current research directions and the issues that are still under study.

2. Existing Classifications

Multi-channel MAC protocols have been classified in the literature according to several criteria. Firstly, the protocols are classified according to the periodicity of channel assignment [6]: fixed channel assignment, semi-dynamic channel assignment, and dynamic channel assignment. Each of these protocols assigns channels in a centralized or distributed manner.

In fixed channel assignment approaches, nodes use the same channel for a long duration. The basic idea of fixed channel assignment approaches is to group the nodes into different clusters such as each cluster uses only a single channel which is different from the channels that are assigned to the other clusters. This helps avoiding inter-cluster interferences but does not solve intra-cluster interferences. The fixed channel assignment protocols do not allow broadcast communications which is a very constrained restriction and affects many WSN routing protocols and applications where broadcasting is usually needed. In semi-dynamic assignments, nodes are assigned fixed channels but they switch between channels in order to communicate with other nodes. On the other hand, semi-dynamic channel assignment needs a coordination of channel switching between the sender and the receiver in order to be on the same channel at the same time. In dynamic channel assignment, nodes switch channels before each transmission. They require precise time synchronization and in practice channel scheduling overhead and switching delay cannot be ignored because of frequent channel switching. In centralized protocols the channel and slot allocation for the whole network is managed by a central node responsible for planning all the transmissions. While on the other hand, in the distributed protocols, each node chooses its own communication channel and timeslot without the need of a central node.

In addition, protocols are also classified according to schedule-based or contention-based MAC protocols [7]. Some protocols try to schedule all transmissions in the network; these are contention-free MAC protocols that are based on a TDMA approach (Time Division Multiple Access) [8]. In schedule-based MAC protocols, there are no collisions but these protocols suffer from the overhead of the control messages. Other protocols adopt asynchronous transmissions, these are contention-based MAC protocols that are based on CSMA/CA (Carrier Sense Multiple Access for with Collision Avoidance) [8]. This type of protocols is more flexible and does not require a strict control message but suffers from data loss due to collisions.

In this paper, we will specify for each studied proposition to which class of protocols it belongs.

3. IEEE 802.15.4 Standard

The IEEE 802.15.4 standard is originally designed for Wireless Personal Area Networks (WPAN). It defines the physical layer and the MAC layer of the protocol stack for WPAN. It has been developed to enable low cost and low power communications for applications in a wide range of fields such as industrial, agricultural, vehicular, and medical sensors fields. It has become widely adopted by several standards such as ZigBee [9], ISA100.11a [10], and WirelessHART [11].

The physical layer operates in three industrial, scientific and medical (ISM) bands and has a total of 27 channels divided into 16 non-overlapping channels at 2.4 GHz with a data rate of 250 Kbps, 10 channels at 902 to 928 MHz with a data rate of 40 Kbps, and one channel at 868 to 870 MHz with a data rate of 20 Kbps. However, only the 2.4 GHz band operates worldwide, the others are regional bands. The 868-870 MHz band operates in Europe, while the 902-928 MHz band operates in North America and Australia.

The 2.4 GHz band generates the highest radio data rates and has the most potential for large scale WSN applications [12].The protocol can make use of multi-channel communication to reduce the effects of interferences generated from its own activity or interferences induced by activities due to co-existing networks that share same parts of the spectrum such as IEEE 802.11 [13]. Fig. 5 shows an example of 3 IEEE 802.11 channels used that overlap with the IEEE 802.15.4 channels.

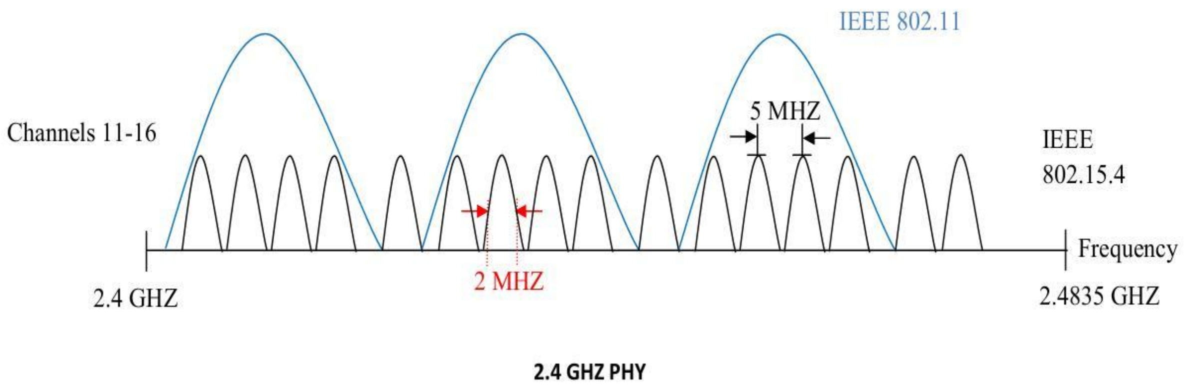

Figure 5. IEEE 802.15.4 channels in 2.4 GHZ ISM band overlap with channels 1, 6 and 11 of IEEE 802.11.

The MAC layer uses slotted or unslotted CSMA/CA to access the medium depending on the operation mode: Beacon-enabled or Non Beacon-enabled modes. The IEEE 802.15.4 standard supports two types of topologies: the star topology and peer-to-peer topology. The star topology is composed of a central node, called the PAN coordinator, and end-devices. The end-devices communicate with each other through the PAN coordinator. The size of the network in a star topology is limited. The peer-to-peer topology is composed of three types of nodes: PAN coordinator, coordinators and end-devices. Each entity except end-device can exchange messages with nodes that are in its communication range.

In IEEE 802.15.4, contention within the network is not resolved since all the nodes communicate on the same channel. The IEEE 802.15.4e [14] version of the standard specifies a channel hopping mechanism on the MAC layer level. This version will be discussed in the next part of the paper.

4. Existing work on multi-channel communication in WSNs

In what follows we will summarize some of the most known multi-channel MAC protocols proposed for WSNs and that are applicable for the IEEE 802.15.4 standard. For each protocol, we describe the main advantages and specify to which class of protocols it belongs depending on the channel allocation method and channel access algorithm. Performance evaluation is also highlighted when available. A comparison summary is given in Table 1.

4.1 Multi-Channel MAC protocol (MCMAC)

In [15], authors propose MCMAC, a coordinator-based centralized multi-channel MAC protocol based on TDMA. It uses a dynamic channel assignment approach for channel allocation. The goal of this protocol is the energy efficiency. The network is divided into clusters. Nodes in the same cluster are synchronized. A cluster contains not more than 64 sensor nodes. MCMAC also assumes that there are many sink nodes in the network. Time is divided into cycles. Each cycle consists of an active period and a sleep period. The active period consists of four phases: synchronous beacon, transmission request, channel schedule, and data transmit. The Cluster Heads (CHs) negotiate to reserve a contact-time for inter-CH communications in the sleep period on a control channel. CHs send the synchronous beacon signal at the beginning and the end of the active period on the control channel in order for the nodes to adjust their wakeup clocks. The CHs switch to listening mode during the transmission request phase, which is divided into several timeslots. The number of timeslots is equal to the number of the cluster member nodes. The timeslots are assigned in accordance with the sensor node ID such that the first slot belongs to the smallest node ID. CHs collect request messages from the cluster members, and then distribute channels to both the source and the destination nodes. After receiving a schedule from the CH, node pairs communicate on the appointed channels. MCMAC was simulated using OMNET++. Energy efficiency is achieved by putting to sleep all the nodes of the neighboring clusters while a certain cluster is active.

This mechanism decreases concurrency and inter-cluster interference, but increases latency in the network. Before each transmission, a channel allocation request must be sent to the CH which increases overhead and energy consumption. In addition, inter-cluster communications are not well detailed in the paper and the slots reserved for the communication between CHs are not sufficient for negotiation and inter-cluster traffic relaying.

4.2 Multi-channel Clustered LMAC Protocol

In [16] authors propose a distributed multi-channel MAC protocol based on LMAC (a TDMA-based protocol) that uses a semi-dynamic channel assignment approach for channel allocation. It aims at increasing parallel transmissions in dense WSNs. The method is composed of two phases. During the first phase, nodes select timeslots according to the single-channel LMAC [17] rules which ensures that a timeslot is only reused after at least 2-

hops. If all the time slots on the basic channel are exhausted, channel selection takes place. The second phase is based on 2-hop neighborhood information where nodes select timeslot/channel pairs to communicate on. Before choosing timeslot/channel pairs, a node scans different channels for bridge node discovery which also helps the node to discover all the occupied timeslots on different frequencies. The performance of the proposed multi-channel MAC protocol is evaluated through theoretical analysis and simulations using Omnet++. Results show that the use of multiple channels decreases the number of active nodes and reduces collisions.

On the other hand, if two neighbor nodes are using different channels, they must communicate through a bridge node which increases packet latency and energy consumption. In addition, in the second phase broadcasts are not supported, if a node is addressed by two neighbors on different channels in the same timeslot it can communicate with only one of them which causes bandwidth wastage.

4.3 Time-Frequency MAC protocol (TFMAC)

In [18] authors propose a hybrid MAC protocol named TFMAC. It is a distributed TDMA-based protocol that uses a semi-dynamic channel assignment approach for channel allocation. It employs a quick channel hopping mechanism. It requires time synchronization and it uses single half duplex transceiver. The goal is to increase network throughput. Time is divided into fixed frames, and each frame is composed of a contention access period and a contention-free period. In contention access periods, nodes monitor the default frequency channel and exchange control messages to maintain neighborhood information. In contention-free periods, nodes exchange data messages. Each contention-free period is divided into N time slots. Slots are assigned by exchanging control messages during the contention slot at the beginning of each time frame. The TFMAC protocol consists of two aspects: frequency assignment and media access. The frequency assignment is used to assign available frequencies to nodes for data reception, while media access scheme establishes collision free media assess schedules, in time and frequency domains. After the frequency exchange, nodes set up timetables such that transmissions from the nodes are conflict-free in time and frequency domains. TFMAC uses a simple channel assignment scheme with k available channels. Slot assignment is performed in a distributed way without the need of a central entity. Nodes are able to select their own receiving channels and a set of k transmission slots for sending data packets to their neighbors. Authors compare the protocol with a single-channel TDMA. Simulations using C++ show that TFMAC improves the average delay and the maximum network throughput.

TFMAC suffers from a high overhead due to the distributed slot/channel selection in the two-hop neighborhood, but this aspect has not been evaluated.

4.4 Hybrid MAC Protocol (HyMAC)

In [19] authors propose HyMAC as a hybrid centralized TDMA/FDMA MAC protocol. It uses a semi-dynamic channel assignment approach for channel allocation. The goal of HyMAC is to provide high throughput and small bounded end to end delay. The communication period in HyMAC is a fixed length TDMA cycle composed of a number of frames. Each frame is equally divided into several fixed timeslots. A fixed number of consecutive slots in each cycle starting, from its beginning, form the scheduled slots while the remaining slots of that cycle are contention access slots. In HyMAC, a base station performs a breadth first search (BFS) algorithm in order to assign for each node an appropriate channel as well as a specific timeslot. Scheduled nodes can communicate in a collision free manner. Nodes turn off their radios when it is not used in order to save energy.

Authors compare the protocol with MMSN protocol in terms of number of potential conflicts. Results show that HyMAC is interference free even when there are only 2 frequencies available while MMSN suffers from the communication interference. Also authors compare HyMAC with RT-Link [20] which is shown to support real time streaming for voice over sensor networks. Both protocols were implemented on FireFly platform which uses CC2420 radio modules. Results show that HyMaC improves the performance in terms of required timeslots.

Some important aspects are not addressed in this paper such as how to maintain time synchronized communication and how new nodes join the network.

4.5 Tree-Based Multi-Channel Protocol (TMCP)

In [21], authors describe a centralized Tree-based Multi-Channel Protocol (TMCP) for data collection applications based on CSMA/CA. It uses a fixed channel assignment approach for channel allocation. The whole network is partitioned into multiple sub-trees having the base station (BS) as a common root where each sub-tree is allocated a different channel as shown in Fig. 6. TMCP can work with a small number of channels and without the need for time synchronization. It uses a greedy algorithm which decreases the radio interference. TMCP has three components, Channel Detection (CD), Channel Assignment (CA), and Data Communication (DC). CD finds available orthogonal channels. CA partitions the whole network into sub-trees and allocates a different channel to each sub-tree. DC manages the data collection through each sub-tree. TMCP is tested using MicaZ motes and simulated using GloMoSim in order to evaluate its performances. Results show that TMCP improves the throughput while keeping high packet delivery ratio and low latency.

On the other hand, TMCP blocks the direct communications between nodes belonging to different sub-trees which is an inconvenient restriction. In addition, communications inside the sub-tree are contention based where CSMA/CA algorithm is used. The difficulty remains to manage communications between sub-trees due to the use of different frequencies in a permanent manner.

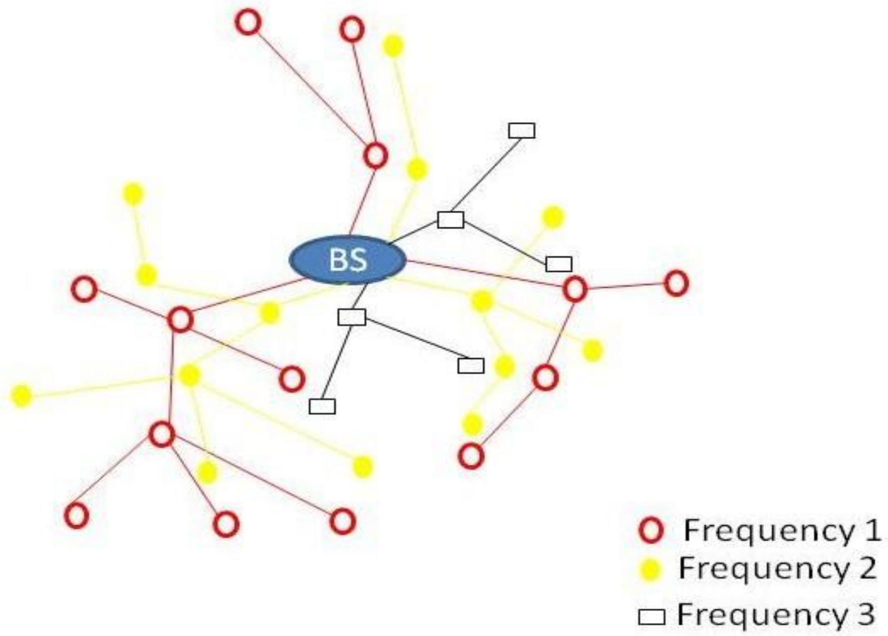

Figure 6. Network topology of TMCP.

4.6 Time Synchronized Mesh Protocol (TSMP)

TSMP [22] is a centralized TDMA-based channel hopping protocol. It uses a dynamic channel assignment approach for channel allocation. It uses a central coordinator that retrieves the neighbor lists of all the nodes in the network in order to allocate conflict free timeslots and communication channels for each node. TSMP allows scheduling using all available channels in order to resist against interferences and persisting multi-path fading. It is designed to improve the data transfer reliability by combining time, frequency, and routing diversity. Different links use different channels and the same link hops during its lifetime across different channels. In [23] authors evaluated TSMP and showed the advantages of using a channel-hopping solution as opposed to a single channel solution based on real world measurements. Blind channel-hopping, which consists on hopping over all available channels of IEEE 802.15.4, improves connectivity and reduces the average number of transmissions needed to hop from node to node by 56% and the portion of nodes in the network which change routing parent between two instances in time by 38%. Also, authors showed that using white listing, which consists on choosing the channels with the highest delivery rate, on a link-by-link basis improves the performance compared to a blind channel hopping. The IEEE 802.15.4e standard based its Time Slotted Channel Hopping (TSCH) MAC protocol on TSMP as well as both wireless industrial standards WirelessHART and ISA100.11a. In addition, ISA100.11a adopts a variation of TSMP which is a hybrid MAC for asynchronous medium access where timeslots of 250 ms are allocated for groups of nodes that contend using CSMA/CA to access the channel.

The multi-hop synchronization mechanism used in TSMP is not detailed and authors do not explain how the synchronization message is propagated. TSMP also suffers from the lack of scalability because of the rigid TDMA segmentation. The introduction of a new node in the network would take too much time before it can start sending data. The new node needs to guess on which channel it should listen. This issue is not discussed and the absence of a control channel makes it difficult for nodes to be able to know on which channels they neighbors are working.

4.7 A Practical Multi-Channel MAC Protocol

In [24], authors proposed a distributed protocol. It uses a dynamic channel assignment approach. The network is divided into clusters and authors used heuristics and feedback control approaches in a distributed and asynchronous manner in order to assign channels to clusters. The authors take into account the real channel switching overhead of the hardware. In order to avoid channel switching overhead, authors propose to form clusters according to the exchanged traffic. The use of new channels is done only when it is needed. A node switches channel in two cases. First case is when it detects that the current channel is overloaded according to its packets loss ratio. Nodes that have a better view of network traffic have preference to switch channel first to initiate the cluster split. This allows neighbors who have heavy traffic destined to that node to switch to the same channel. This phase is named channel expansion. The second case takes place when a channel is no longer overloaded, nodes on this channel invite those from the next channel in the channel list to switch to the underutilized channel. This phase is named channel shrinking. The proposed protocol avoids network congestion and achieves performance improvements according to the evaluation done on the proof of concept tested with MicaZ motes. Throughput increase of as much as 50% is reported in dense networks compared with a single channel use.

On the other hand, nodes periodically broadcast status messages to their neighbors which is not a negligible overhead and thus energy efficiency may become an issue in large scale networks. The other drawback of this protocol is the channel choice which is based on a fixed channel list instead of taking into account the possibility of spatial reuse of channels.

4.8 An Energy-Efficient Multi Channel MAC Protocol (Y-MAC)

Y-MAC [25] is designed in order to reduce latency. It is a distributed TDMA-based multi-channel MAC protocol. It uses a dynamic channel assignment approach. Authors adapted a distributed method based on algorithms proposed in LMAC and MMSN. Timeslots are assigned to receivers. Y-MAC utilizes a hybrid access method where time is divided into cycles. Each cycle is composed of a broadcast period and a unicast period as shown in Fig. 7. At the beginning of the broadcast period, nodes wake up in order to exchange broadcast messages. Nodes exchange the time remaining in the current frame period in order to maintain synchronization. Y-MAC uses a slot allocation vector in order to achieve timeslot assignment. It allows new nodes to join the network and to assign timeslots in a dynamic way. This vector is used for storing information about the slots occupied by the neighbors. This vector is then broadcast with the control messages to 1-hop neighbors. In order for a node to allocate a free timeslot in its 2-hop neighborhood, it executes an OR operation over all the slot allocation vectors received from its neighbors. If there are many available timeslots, one of them is randomly selected; otherwise several nodes should share the same timeslot. At the beginning of each timeslot, potential senders to the same receiver compete in order to access the medium using a CSMA/CA algorithm. Multiple packets are sent successively on different channels, the receiver and the sender hop to a new channel according to a predetermined sequence. Y-MAC reduces latency by offering the possibility for nodes that were not able to send their traffic to compete in a consecutive slot. All potential senders that have pending frames destined to the same receiver also hop to the same channel and compete again. Y-MAC was implemented using the RTOS operating system on the TmoteSky motes. Authors compared Y-MAC with LPL [26] and Crankshaft [27] in single hop environments, under high traffic conditions (1 packet per second). Results show that Y-MAC and Crankshaft have similar latency and duty cycle and both protocols outperform LPL. Y-MAC achieves better reception rate under high traffic conditions compared to the other two. Authors also compared Y-MAC with Crankshaft in multi-hop environments. Results show that the duty cycle of Y-MAC is slightly higher than Crankshaft. Also the average per hop delivery latency of Crankshaft rises faster than Y-MAC as the traffic load increases and YMAC outperforms Crankshaft in terms of data reception rates.

On the other hand, the channel allocation method is not detailed in the paper, authors only insist on not using the same channel in 1-hop neighborhood which leads in high interferences due to 2-hop interferences. Also the side effects that appear within the usual congestion area around the sink nodes with high data rate scenarios are hard to solve.

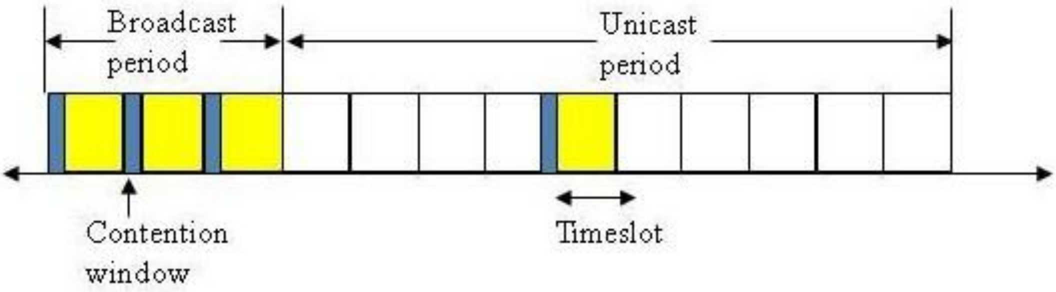

Figure 7. Each Y-MAC cycle is composed of a broadcast period and a unicast period.

4.9 Multi-Frequency Media Access Control protocol (MMSN)

In [28], authors proposed MMSN protocol which aims at increasing parallel transmissions. It is a distributed protocol that combines FDMA and CSMA mechanisms. It uses a semi-dynamic channel assignment approach for channel allocation. In the protocol, different strategies for channel assignment are evaluated and analyzed: exclusive frequency, even-selection, eavesdropping, and implicit-consensus. In the exclusive frequency assignment strategy, the number of frequencies should be equal to or greater than the number of nodes within two hops. Nodes exchange their identities (IDs) in their 2-hop neighborhood. Nodes choose frequencies in the increasing order of their ID values. If a node has the smallest ID in its 2-hop neighborhood, it chooses the smallest frequency among those available and then it sends the chosen frequency to its 2-hop neighbors. This strategy ensures that nodes in any 2-hop neighborhood are assigned different frequencies, but it induces high communication overhead due to the ID and frequency exchange between 2-hop neighbors using CSMA/CA. The even-selection strategy is more suitable for dense WSN where the number of frequencies is smaller than the number of nodes within two hops. It is similar to exclusive frequency strategy, but when all frequencies are already chosen in a 2-hop neighborhood, a node randomly chooses one of the least chosen frequencies. Hence, it does not ensure that nodes in any 2-hop neighborhood are assigned different frequencies. In the eavesdropping strategy, each node takes a random backoff during which it waits for its 1-hop neighbors to choose their frequencies. When its backoff expires, it randomly chooses one of the least chosen frequencies within one hop. This strategy has less communication overhead compared to the first two strategies, but it only collects frequencies information within 1-hop neighborhood and during a limited random time interval which results in more conflicts and more interferences. In the implicit-consensus strategy, nodes exchange their identities in their 2-hop neighborhood. For each frequency, each node calculates a random number for itself and a random number for each node in its 2-hop neighborhood using the same pseudo-random number generator. A node wins current frequency if its random number is the highest among all the other random numbers. It then broadcasts its frequency to the 2- hop neighbors. This strategy guarantees smaller overhead but assumes a high number of available frequencies. The performance of MMSN is evaluated through simulations using GloMoSim simulator and compared with CSMA/CA. In this evaluation, MMSN uses even selection for channel allocation. When the number of channel increases from 1 to 4, packet delivery ratio increases from 95.2% to 97.3%, aggregate MAC throughput increases by 119% from 239Kbps to 523Kbps and the channel access delay decreases to 0.021s, which is 37.5% of the delay when only 1 frequency is available. Results also show that when the system loads increases from 15 CBR streams to 50 CBR streams, CSMA/CA has a decreased packet delivery ratio from 98.3% to 95.4%, while MMSN does not have such an obvious packet loss.

At the beginning of each timeslot, nodes contend for the medium to broadcast traffic on a common broadcast channel. When a node transmits a packet, it switches between its own channel and the destination channel during the preamble sending time, which results in increasing the message delay and the protocol overhead due to frequent channel switching.

4.10 Traffic-Aware Channel Assignment mechanism

In [29], authors propose a distributed Traffic-Aware Channel Assignment mechanism. It is a CSMA/CA multi-channel MAC protocol. It uses a semi-dynamic channel assignment approach. Each node has a traffic weight based on their data rates. Nodes collect the IDs and the traffic weights of all neighbors within two hops. They make channel decisions in the decreasing order of their traffic weights. That means if a node presents the greatest traffic weight in its 2-hop neighborhood, it chooses the channel with the least load among available ones. If two nodes have the same traffic weight, the node that has the smallest ID makes the decision first. When a node chooses a channel, it sends the chosen channel to its 2-hop neighbors. The traffic-aware frequency assignment is compared with two frequency assignment methods of MMSN: even-selection and eavesdropping. Simulations show that the proposed protocol achieves in average 13.5% higher aggregate throughput. It enhances the packet delivery ratio while at the same time reducing channel access delay and radio interference.

Authors suppose that the data rate is constant and predictable in the future. This mechanism has high communication overhead due to the exchange of IDs and traffic weights between 2-hop neighbors and it does not cope well with traffic load fluctuation.

4.11 Multi-Channel LMAC Protocol (MC-LMAC)

In [30], authors propose Multi-Channel Lightweight MAC protocol which is a distributed schedule-based multi-channel MAC protocol based on the single channel LMAC [16]. It uses a semi-dynamic channel assignment approach for channel allocation. MC-LMAC achieves interference free and collision free parallel transmissions over multiple channels. It is made and designed in order to provide a high throughput and high delivery ratio by coordinating multi-channel transmissions. MC-LMAC guarantees that the same slot/channel pair is not simultaneously used within a two-hop neighborhood. Each node manages an occupied slots vector per channel with a length equal to the number of timeslots. This vector is used for storing the information about the slots occupied by the neighbors. Each bit in the occupied slots vector is set if the timeslot at the same position is occupied. This vector is then sent to 1-hop neighbors. In order for a node to choose a channel, it executes an OR operation over all the occupied slots vectors received on a certain channel in order to find a free timeslot. Fig. 8 shows an example with 7 nodes, 2 channels and 5 timeslots. All the nodes have selected a timeslot and a channel except for the central node. The central node does an OR operation on the occupied slots vectors collected from its neighbors and detects that it can use slot number 5 on channel 2. The performance of MC-LMAC is evaluated through simulations using GloMoSim simulator. Results show that by increasing the number of channels a better throughput is achieved and in particular conditions it appears to be approaching the maximum theoretical throughput.

On the other hand, MC-LMAC suffers from the overhead of the control messages that are exchanged in order to discover the channels used in the different TMDA slots in 2-hop neighborhood. The problem increases as the network density increases.

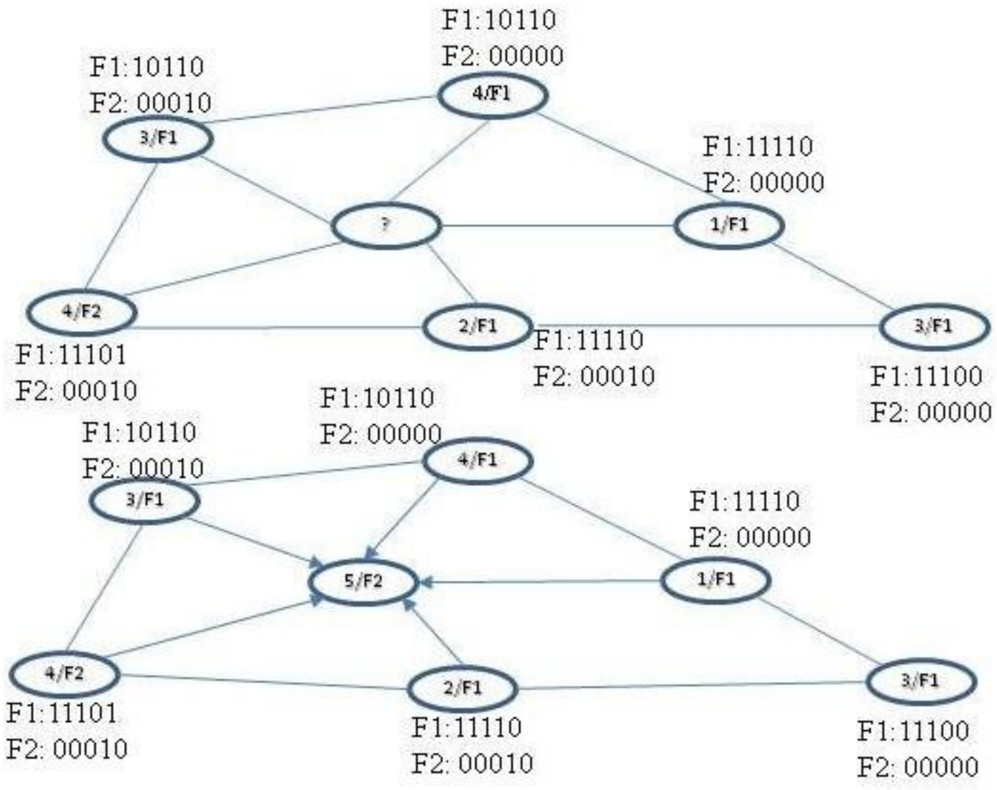

Figure 8. Slot/Channel pair allocation in MC-LMAC using occupied slot vectors.

4.12 Low Overhead MAC Protocol Much MAC (MuChMAC)

In [31], authors propose MuChMAC protocol. It is a distributed low-overhead Multi-Channel MAC protocol. It uses a dynamic channel assignment approach. It combines TDMA and asynchronous MAC techniques. Time is divided into slots. A node is able to independently choose its receiving channel switching sequences based on its ID and the current slot number using a pseudo-random generator. A broadcast slot is inserted every n slots. These broadcast slots also follow a pseudo-random channel hopping sequence but they are the same for each node. A sender is thus able to calculate the channel of the receiver. It switches its radio transceiver to the receiver channel and starts to send small preambles messages. When the receiver wakes up, it hears a preamble and it acknowledges the sender that it is awake. Then the data frame can be sent. MuChMAC ensures waking up the receiver and the sender within the same slot using loose global time synchronization and a fixed upper bound on clock drift. MuChMAC is tested using Sentilla JCreate motes in order to evaluate its performances. Authors compare the protocol with X-MAC [32] which is the standard asynchronous Contiki MAC layer. Results show that the protocol is energy efficient and improves reliability.

On the other hand, the channel allocation is based on a random mechanism that does not take into consideration the channel usage in the neighborhood which might lead into a high collision rate.

4.13 Multichannel optimized delay time slot assignment (MODESA)

In [33] authors propose MODESA which is a centralized schedule-based algorithm that aims at optimizing slot assignment for raw data convergecast in a multi-channel network in order to reduce the TDMA gathering cycle. MODESA uses a dynamic channel assignment approach. The goal of this algorithm is to determine the minimum number of slots in order to provide a high throughput. MODESA runs on the ordered set of nodes according to their priority. Nodes have a dynamic priority which is equal to the number of packets they have in their buffers at the current iteration. Non-conflicting nodes are allocated the same channel. Any other node in the sorted set is assigned the same timeslot but on a different channel if it conflicts with nodes already assigned to the current slot. The performance of MODESA is evaluated through simulations that show that MODESA needs a small buffer size and reduces the number of radio switches. Authors do not discuss how to maintain time synchronization over a multi-hop network, and do not explain how the network is created.

MODESA suffers from the overhead of control messages that are exchanged in order to schedule all transmissions, especially when repetitions need to be taken into account in case of data loss.

4.14 Hybrid Multi-channel MAC Protocol (HMC-MAC)

In [34], authors proposed HMC-MAC, which is a Hybrid Multi-channel MAC Protocol that tries to improve the overall network performance in WSNs. It is a distributed protocol that uses a semi-dynamic channel assignment approach for channel allocation. They defined a new method for channel allocation that enables nodes to choose the most convenient channel in their 3-hop neighborhood in order to minimize the risk of interferences. HMC-MAC takes advantage of the flexibility offered by CSMA/CA to maintain a dynamic and scalable network, of the synchronous activity of TDMA to propagate multi-hop control messages, and of the parallel transmissions over different channels provided by FDMA to enhance the network performance. Authors assume that the risk of interferences reaches 3-hop neighborhood and this is due to the use of MAC layer acknowledgements. Time is divided into cycles that are divided into synchronization and communication intervals. A special node labeled Network Coordinator (NC) broadcasts a beacon that is propagated in a multi-hop manner to reach all the nodes of the network during the synchronization interval. During the communication interval, nodes exchange messages in order to route data frames towards the final destinations according to their depth in the topology. 2-hop and 3-hop neighbor lists and channels allocated in the 2-hop and 3-hop neighborhood are exchanged using bitmaps. These bitmaps are included in the beacon frame. In order for a node to choose a channel, it first tries to find a free channel among the channels already used by its 3-hop neighborhood. When it does not find a free channel in its 3-hop neighborhood, it tries to find a free channel in its 2-hop neighborhood. In case there are no available channels in its 2-hop neighborhood, the node tries to find a free channel in its one-hop neighborhood. Finally, if it does not find a free channel, it randomly takes a channel among the less used channels in its 1-hop neighborhood. Simulation results using NS2 simulator showed that HMC-MAC provides smaller interference rate compared to other allocation methods based on random choice and 2-hop neighborhood information. In [35], authors evaluated the efficiency of the channel allocation method in a data collection application scenario and results showed that HMC-MAC achieves fewer conflicts than other methods based on 2-hop and 3-hop neighborhood.

On the other hand, results in terms of packet loss, latency and throughput are not available. HMC-MAC does not cope well with high mobility.

5. Open Issues in Multi-Channel MAC Protocols

Although a lot of work has been done in this domain, many challenges remain unsolved and require more investigations. In what follows, we will highlight the aspects that are still open and which constitute potential research directions. We identified some aspects related to the protocol design such as multi-hop synchronization, compromise between overhead and determinism, adaptation to the application profiles, and neighbourhood discovery. Other aspects such as overhead evaluation, node design, and networks co-existence are also discussed.

5.1 Multi-hop synchronization

Most of the TDMA-based protocols suffer from unrealistic considerations for timeslot synchronization over a multi-hop network. For most cases, nodes that are used in WSNs must be low cost and energy efficient. This objective has several consequences on the design of a node on the hardware architecture and the choice of the components as well. This is why the existing solutions based on IEEE 802.15.4 are equipped with a relatively slow clock that provides a low capacity to manage time in a fine-grained way. Hence, the precision of both the transceiver and the processor is not enough to establish a synchronization using the time of arrival of the frames (such as the Start of Frame Delimiter (SFD) interruption offered by most of the IEEE 802.15.4 compliant transceivers). One of the solutions to overcome this problem is to include a significant guard time interval when considering synchronization over a multi-hop network which causes a loss of bandwidth and energy.

5.2 Compromise between overhead and determinism

Most deterministic multi-channel MAC protocols require high control traffic exchange between nodes in order to establish an appropriate slot/channel allocation. It is often based on neighborhood discovery and on the offered load of each node (data transmission rate). Adding to that, the possible dynamic routing process that might change the amount of packets one node is asked to route. Hence, in order to adopt a fair timeslot allocation, these information must be accurate and updated when needed to avoid overloading nodes that do not have enough timeslots or underloading nodes with available unused allocated timeslots.

5.3 Adaptation to the application profiles

Designing a generic MAC protocol that suits all application profiles demands a great compromise between performance and suitability. When dealing with a data collection application profile, it is clear that slot reservation and allocation can be easily established to route data towards the sink in an optimal way. On the other hand, when dealing with applications where any node can be a destination, slot allocation would be more complex as traffic might travel in all directions. The crosslayer design between the application profile and multi-channel MAC layer slot allocation algorithm is an open research topic that helps adapt the mechanism to better suit traffic flows.

5.4 MAC layer Acknowledgements and 2-hop neighborhood

Most of the studied protocols consider 2-hop neighborhood in their timeslot allocation algorithm. This is not enough when MAC layer acknowledgements are used. The use of MAC layer acknowledgements affects the correctness of the allocation algorithms, and this is very often neglected. For when a receiver has to immediately acknowledge every frame that is received (which is the case of the IEEE 802.15.4 transceivers when the acknowledgement is requested), it becomes a sender during the slot where it is considered as a receiver.

5.5 Lack of overall control traffic evaluation

As discussed previously, control traffic is needed in order to collect information that helps achieve better slot/channel allocation. Most evaluations are often done to show the achieved performance enhancement once all the needed information is exchanged. On the other hand, authors often neglect the cost of this control traffic. Exchanging this traffic is often done using CSMA/CA which is prone to collisions, and thus, is not energy efficient. Time of convergence (time needed to collect all the necessary information) is also an important issue from which protocols suffer and cause bandwidth wasting. Most of the network topologies chosen for evaluation are stationary. Even though nodes are not mobile, this hypothesis has to be reconsidered. The evaluation process depends on the evaluation tools, for example, some simulators do not include accurate wireless medium behavior and thus time of convergence is often very optimistic.

5.6 Multi-antenna

Multi-channel protocols aim at enhancing the overall network performance but when they consider one sink (or several sinks) in the network, the throughput is often limited to the receiver capacity of the sinks. If sinks are equipped with one half-duplex antenna, it can only receive messages coming from one node at a time. Thus, the use of the multiple channels loses a part of its interest. One solution would be to consider sinks as multi-antenna nodes that are able to receive simultaneously from different nodes on different channels. This issue is still under study for the coexistence of multiple radio transceivers in centimetric dimensions. The characteristics of the filters used to select a channel among all the channels provided by IEEE 802.15.4 compliant devices do not prevent electromagnetic interference, thus, MAC protocols cannot use arbitrary channels on a multi-antenna node.

5.7 Wireless networks co-existence

The dynamic aspect of the channel hopping should be an important issue to be taken into account not only to manage intra-network interferences but also interferences with neighboring networks or devices operating in the same 2.4 GHz ISM band. Any communication protocol that is unable to cope with the dynamic channel occupation in its environment will be very vulnerable. Protocols should be able to intelligently choose and hop between the available channels in order to better resist against co-existent technology interferences.

6. Conclusion

In this survey paper, we studied different multi-channel MAC protocols designed for WSNs and compliant with IEEE 802.15.4 standard. The use of multiple channels enhances the overall network performance by avoiding inner and outer interferences and allowing non-interfering simultaneous transmissions. We highlighted the main contribution of each protocol and discussed their weaknesses. Different classifications have been proposed in the literature, based on the coordination method for assigning slots and channels, the type of medium access sharing or the periodicity of channel switching. We specified for each protocol to which type of protocols it belongs and we summarized the essential criteria in a table including all the studied protocols. We ended the study with an open discussion about current research directions in the multi-channel MAC protocol domain and highlighted the main issues that are left unsolved. With the increasing demand of wireless communications, cognitive radio protocols that are able to adapt their channel usage depending on the environment and on co-existing interference technologies is a promising research area for wireless sensor networks.

Table 1. Comparison summary of Multi-Channel MAC protocols.

Protocol	Comparison multi-channel MAC protocols for WSNs								
	Year of submission	Frequency allocation method	Synchronization	Medium access	Broad- cast support	Channel used for data transfer	Channel allocation	Evaluation method	Objective
MCMAC [15]	2006	Centralized	Required	Schedule-based (TDMA)	Inside clusters	Appointed channel	Dynamic	Simulations (OMNET++)	Energy efficient
Multi-Channel Clustered LMAC [16]	2006	Distributed	Required	Schedule-based (TDMA),LMAC	Yes	Sender	Semi-dynamic	Simulations (OMNET++)	Increase parallel transmission in WSN
TFMAC [18]	2007	Distributed	Required	Schedule-based (TDMA)	Yes	Receiver	Semi-dynamic	Simulations built in C++	Increase network throughput
HYMAC[19]	2007	Centralized	Required	Schedule-based (TDMA)	No info.	Sender	Semi-dynamic	Simulations	Improve throughput and end-to-end delay
TMCP [21]	2008	Centralized	Not Required	Contention-based(CSMA)	Inside branch	Sub-tree	Fixed	Simulation (GloMosim)	Efficient data collection
TSMP [22]	2008	Centralized	Required	Schedule-based (TDMA)	Yes	Appointed channel	Dynamic	Developed in a managed network	Improve the data transfer reliability by combining time frequency and routing diversity

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Protocol	Comparison multi-channel MAC protocols for WSNs								
	Year of submission	Frequency allocation method	Synchronization	Medium access	Broad- cast support	Channel used for data transfer	Channel allocation	Evaluation method	Objective
Practical [24]	2008	Distributed	Not Required	No Info.	Between clusters	Receiver	Dynamic	Implementation Micaz +simulation	Efficiently utilize Multiple channels
Y-MAC [25]	2008	Distributed	Required	Hybrid	Yes	Receiver	Dynamic	RTOS operating system on the tmoteSky motes	Reduce latency
MMSN [28]	2010	Distributed	Required	Hybrid	Yes	Receiver	Semi-dynamic	Simulation (GloMosim)	Increase parallel transmission
Traffic aware [29]	2010	Distributed	Required	Hybrid	Yes	Receiver	Semi-dynamic	Simulations	Consider nodes traffic volumes
MC-LMAC [30]	2010	Distributed	Required	Schedule-based (TDMA)	Yes	Sender	Semi-dynamic	Simulation (GloMosim)	Provide a high throughput
Much MAC [31]	2010	Distributed	Required	Schedule-based (TDMA),X-MAC	Yes	Receiver	Dynamic	Sentilla and create motes	Improve bandwidth
MODESA [33]	2012	Centralized	Required	Schedule-based	Not clear	Sender	Dynamic	Simulations	Reduce the TDMA gathering cycle
HMC-MAC[34]	2013	Distributed	Required	Hybrid	Yes	Receiver	Semi-dynamic	NS2	Improving throughput

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