MC-LMAC: A Multi-Channel MAC Protocol for Wireless Sensor Networks

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***Abstract*—In traditional wireless sensor network (WSN) applications, energy efficiency is considered to be the most important concern whereas utilizing the use of bandwidth and maximizing the throughput are of secondary importance. However, recent applications, such as structural health monitoring, require high amounts of data to be collected at a faster rate. We present a multi-channel MAC protocol, MC-LMAC, designed with the objective of maximizing the throughput of WSN by coordinating transmissions over multiple channels. MC-LMAC takes the advantage of interference and contention free parallel transmissions on different channels. It is based on scheduled access which eases the coordination of nodes dynamically switching their interfaces between channels and makes the protocol to operate effectively free of collisions during peak traffic. Time is organized into timeslots and each node shall be assigned control over a timeslot to transmit on a particular channel. We analyze the performance of MC-LMAC with extensive simulations. MC-LMAC exhibits significant bandwidth utilization and high throughput while ensuring an energy-efficient operation. Moreover, MC-LMAC outperforms the contention-based multi-channel MMSN protocol, cluster based channel assignment and single-channel CSMA in terms of data delivery ratio and throughput for high data rate, moderate-size networks of 100 nodes.**

I. Introduction

In typical wireless sensor network (WSN) applications it is of interest to extend the network lifetime due to the battery limitations of the sensor devices. As an important source of energy consumption, wireless communication in WSN has received a lot of attention. Especially the MAC protocols [1] have been extensively studied with the objective of energy efficiency whereas throughput, bandwidth utilization, fairness and latency were considered as the secondary objectives [2].

It is usual that bandwidth is not the main concern in traditional low-duty cycle, low-date rate applications. However, it becomes an important concern during certain periods of time when a large burst of packets is generated due to a change in the monitored conditions and needs to be transported in a reliable and efficient manner to a base station. Emerging applications such as intruder detection [3], structural health monitoring [4], etc. require data transfer at a higher rate by utilizing the use of the limited bandwidth. Moreover, it becomes more common to use sensor nodes that run multiple concurrent applications which also results in higher data rate requirements. The common use of WSN will further result in overlapping and co-existing networks which will make the bandwidth an important concern for WSN [5].

The fundamental limitation on the achievable throughput is the limited reuse and/or the wastage of bandwidth due to interference and the half-duplex operation of the radios on the sensor nodes. In general wireless networks, multiple channels have been provisioned to mitigate the effects of interference by assigning different frequency channels to interfering links.

In this paper we investigate the use of multi-channel MAC protocols to improve the achievable throughput of WSN. Although the typical WSN radios operate on a limited bandwidth, the operating frequency of the radios can be adjusted over different channels. Once different channels are assigned to interfering or contending links, more simultaneous transmissions can take place and more data can be delivered to the sink node in limited time.

We first present the challenges and requirements of multi-channel communication from the perspective of WSN. Next, we introduce MC-LMAC (Multi-Channel Lightweight Medium Access Control) which is a schedule-based multi-channel MAC protocol that takes the advantage of interference and collision free parallel transmissions on different channels.[1]

MC-LMAC is designed to provide higher throughput over multiple channels whereas it also meets the traditional requirements of WSN such as energy efficiency and scalability. The main design criteria are based on the single-channel LMAC (lightweight medium access control) which is proved to be an efficient and energy-aware MAC protocol for WSN [6]. A node selects a timeslot and a channel on which it is allowed to transmit. Timeslot and channel selection is fully distributed and guarantees the same slot/channel pair not to be used within the 2-hop neighborhood. A timeslot consists of a control period and a data transmission period. During the control period, all the nodes switch their interfaces to a common channel. The control period is used for notifying the destination about the incoming packet and the channel on which the data transmission will take place such that the receiver should switch its interface. The following are some of the key highlights of this work:

[1] A channel is defined to be a frequency range over which two nodes communicate. We will use the terms "channel" and "frequency" interchangeably in the text.

- We present a review of existing multi-channel MAC protocols for WSN and discuss the requirements and challenges of multi-channel communication.
- MC-LMAC does not only support many-to-one communication towards the sink node but broadcasts and local-gossip operations are also supported, which can be quite challenging in a multi-channel communication environment [7].
- We evaluate the performance of MC-LMAC with extensive simulations in Glomosim [8] and present a large study of comparisons with the MMSN [9] protocol which is a recently proposed multi-channel MAC protocol for WSN. Different from the scheduled communication in MC-LMAC, MMSN provides contention-based channel access. The protocols with completely different designs allows us to study a large set of tradeoffs between different performance metrics. The MC-LMAC protocol achieves better delivery ratio and throughput during high data rate scenarios whereas the MMSN protocol may fail to successfully allocate the medium. Moreover, we compare the performance with CSMA and with a clustering mechanism where the branches of the routing tree are assigned different channels.
- To show the advantages of multi-channel protocols, we compare MC-LMAC and the mentioned techniques with an alternative where the communication takes place on a single-channel but over a larger bandwidth. For further comparisons, we investigate single-channel scenarios with multiple-sink nodes.
- We implement MC-LMAC on the Ambient μNode [10] platform as a proof of concept.

The remainder of the paper is organized as follows: Section II presents the related work. Section III motivates the use of multiple channels in WSN. Section IV introduces the MC-LMAC protocol with the details on channel-timeslot selection and medium access. Section V presents the performance of the protocol for typical WSN traffic patterns in terms of different factors such as throughput and latency. Finally, Section VI gives the concluding remarks.

II. Related Work

A. *Use of Multiple Channels in General Wireless Networks*

The channel assignment problem and multi-channel MAC protocols in wireless networks have been extensively studied for both cellular and ad hoc networks. In cellular networks [11], base-stations use different frequency domains within a cell, while clients share the time domain to access the wireless medium. However, this approach is based on 1-hop channel assignment and is not suitable for multi-hop networks.

Multi-channel communication has been extensively used in multi-hop ad hoc networks to increase the system throughput [12]–[14]. Most of these approaches are based on the IEEE 802.11 protocols; IEEE 802.11a provides 12 independent 54Mbps channels whereas IEEE 802.11b allows 14 channels that are spaced 5MHz apart. However, IEEE 802.11 protocol is very expensive in terms of energy consumption and does not meet the requirements of WSN [9]. Protocols in [15] either assume multiple radios on the nodes or consider radios that can listen on multiple frequencies simultaneously. Protocols [16], [17] can operate with frequency-hopping spread spectrum wireless cards. However, in WSN, usually nodes are equipped with much simpler radios and there is a single radio available on each node. Additionally, typical bandwidth used by WSN radios is limited. Although these protocols perform well in general wireless multi-hop networks, the mentioned constraints of WSN require a different design.

B. *Use of multi-channel communication in WSN*

In WSN domain, there are many MAC protocol proposals which consider single-channel communication [18]–[23]. These protocols perform to be good in single-channel scenarios where the primary design goal is the energy efficiency [1], scalability and adaptability to changes [2].

There are single-channel MAC protocols that aim to provide high-throughput especially with scheduled communication such as Z-MAC [23], Burst-MAC [24]. While these protocols perform well in single-channel scenarios, parallel transmissions over multiple channels can further improve the throughput by eliminating the contention and interference on a single-channel.

Besides multi-channel communication there exist other methods to reduce the impact of interference such as transmission power control [25], creating minimum interference sink trees [26]. In a previous work [27] we have investigated the impact of transmission power control on the network's performance with a realistic setting and found that discrete and finite levels of adjustable transmission power on the radios may not completely eliminate the impact of interference.

1) Challenges and Requirements: In this section we explain the challenges and requirements of multi channel communication from the perspective of WSN and how we address them in our protocol:

- Synchronization: If the channel assignment is done dynamically, i.e. the radios are switching between channels instead of being fixed on one channel, a detailed coordination of channel switching is required between the senders and receivers in order to be on the same channel at the same time. Scheduled access overcomes this complexity and that is where we benefit from the time-slotted communication of single channel LMAC.
- Partitions: If transceivers of two nearby nodes are fixed on different frequencies, they cannot communicate with each other. MC-LMAC uses a common channel during the control period of each timeslot to let the receivers be informed about the requests and about the channels on which the data will be sent.
- Joining the network: A new node joining the network may disrupt the channel organization or may be required to scan all the channels to find the suitable channel to transmit. In MC-LMAC, communication on a common channel at the beginning of each timeslot lets the new

joining node to collect full information about its neighborhood before starting transmission.

- Broadcast support: If the nodes are switching between channels dynamically, it might be problematic to support local broadcasts. However, local broadcasts are important for WSN traffic since sensor nodes may require in-network processing before they transmit the data towards the sink node. In MC-LMAC all the receivers of a broadcast are informed on the common channel at the beginning of each slot.
- Channel switching: The radio can not switch between the channels immediately but takes some time, for instance it is around $650 \mu sec$ for Nordic Nrf905 radio. The timeslot size in MC-LMAC is large enough to accommodate the switching time and the overhead of switching time can be considered as negligible.

2) Existing Work: There exist recent proposals for multi-channel usage in WSN. In this section we discuss the differences between the existing work and our work. One point worth of mentioning is that the performance of existing protocols have been compared against single-channel protocols. In this work, we compare our protocol with example multi-channel protocols via simulations.

Zhou et al. [9], recently introduced the MMSN multi-frequency MAC protocol especially designed for WSN. It is a slotted CSMA protocol and at the beginning of each timeslot nodes need to contend for the medium before they can transmit. On the other hand, in the MC-LMAC protocol we assume a scheduled access where each node is granted a timeslot beforehand and uses this timeslot without contention. Contention based protocols are known to have a lower delay and promising throughput potential at lower traffic loads, which generally happens to be the case in WSN [2]. However, when the network load is high, there is a higher waste of bandwidth from collisions and backoffs. On the other hand, schedule-based communication has the inherent advantage of a collision-free medium access.

MMSN assigns channels to the receivers. When a node intends to transmit a packet it has to listen for the incoming packets both on its own frequency and the destination's frequency. A snooping mechanism is used to detect the packets on different frequencies which makes the nodes to switch between channels frequently. MMSN uses a special broadcast channel for the broadcast traffic and the beginning of each timeslot is reserved for broadcasts. Different from MMSN, MC-LMAC does not require a dedicated broadcast channel. On the other hand, at the start of each timeslot, all the nodes are required to listen on a common channel in order to exchange control information which simply adds to the protocol overhead. But doing so provides many advantages: collision-free addressing, maintaining synchronization, allowing distributed operation of the medium access. Moreover, the control period is much smaller compared to the data period and during the data period the nodes can transmit multiple packets to minimize the overhead.

TMCP [28] is a tree-based multi-channel protocol for data collection applications. The goal is to partition the network into multiple subtrees with minimizing the intra-tree interference. The protocol partitions the network into subtrees and assigns different channels to the nodes residing on different trees. TMCP is designed to support convergecast traffic and it is difficult to have successful broadcasts due to the partitions. Contention inside the branches is not resolved since the nodes communicate on the same channel.

Similar to TMCP, the protocol in [29] uses a control theory approach to assign channels to the clusters of nodes. Initially all the nodes communicate on the same channel and when a channel becomes overloaded nodes migrate to new channels based on the feedback information from the neighbors around.

Y-MAC [30] is another recent multi-channel MAC protocol for WSN. Similarly, it is based on scheduled access. However, timeslots are not assigned to the senders but to the receivers. At the beginning of each timeslot potential senders for the same receiver contend for the medium. Each timeslot is long enough to transmit one data message. If multiple packets need to be transmitted, then the sender and the receiver hop to a new channel according to a predetermined sequence. Other potential senders also follow the hopping sequence of the receiver. As we mentioned, increased contention especially around the sink node with high data rate scenarios is hard to solve with contention based protocols as we further discuss in the rest of the paper.

Another multi-channel MAC protocol for WSN is the HyMAC [31]. Similar to our protocol, HyMAC is also a combination of TDMA and FDMA. However, assignment of timeslots and frequencies is done according to the Breath First Search (BFS) algorithm on a tree topology. However, there remain the open questions such as how to maintain time-synchronized communication, how to resolve collisions or how a new node joins the network.

Table I illustrates a classification of the existing MAC protocols on the discussed topics.

III. MOTIVATION

Theoretically speaking, the throughput capacity of a WSN with n nodes under many-to-one communication pattern can not exceed W/n per node where W is the transmission capacity of the radio [32]. Practically, this bound is usually not achieved due to the half-duplex nature of the radio and due to the increased amounts of contention and interference in dense deployments with multi-hop topologies.

In this section, we study a simple benchmark scenario to show the efficiency of multiple-channels. In Figure 1(a) we present a topology where all the source nodes can directly reach the sink node. Let W represent the capacity of the shared medium. In an idealized setting, aggregate throughput would be W, and each source node should transmit with a capacity of $W/4$. When we switch to a multi-hop scenario which is shown in Figure 1 (b), if there is no interference then with a suitable scheduling mechanism we can achieve the $W/4$ throughput per node. However, if all the nodes interfere with each other, then each node can get only $W/6$ capacity. On

	MC-LMAC	Y-MAC	MMSN	TMCP	HyMAC	[29]
Broadcast Support	+	+	+	No information	No information	No information
Partitions	-	-	-	+	-	-
Medium Access	Scheduled	Scheduled	Slotted Contention	No information	Scheduled	No information
Channel Assignment	Senders	Dynamic	Receivers	Clusters	Senders	Receivers (home ch.)
Channel Switching	Once per ts	Once per ts	Multiple times per ts	No	Once per ts	If needed
Joining Network	Anytime	Anytime	At channel assignment	At channel assignment	At channel assignment	Anytime (scanning needed)

TABLE I
COMPARISONS

the other hand, if nodes can use different channels to transmit then interference can be eliminated and the nodes can reach the $W/4$ capacity.

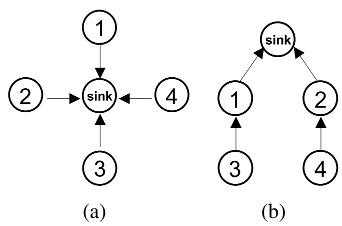

Fig. 1. (a) Single-hop topology used in the benchmark scenario; (b) Multi-hop topology used in the benchmark scenario;

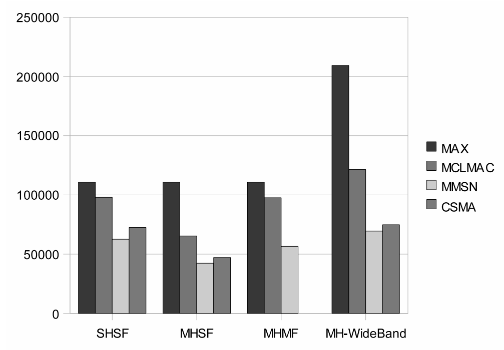

Fig. 2. Benchmark Results

In Figure 2 we show the simulation results from Glomosim [8] for the presented topologies. The vertical axis shows the aggregate throughput in total bits per second received at the sink node, and the abbreviations are as follows: SHSF: Single-hop, single-frequency, MHSF:Multi-hop, single-frequency, MHMF:Multi-hop, multi-frequency. Nodes transmit 32-byte packets continuously (every 2msec) to the sink node (effective data rate is 250kbps). The maximum aggregate throughput, i.e. total amount of data that the sink can receive per unit time from all sources, is calculated as 103896.1 bits per second. When the topology is single-hop and there is a single channel (SHSF), slotted MC-LMAC performs close to the maximum. The only overhead is the control messages sent at the beginning of timeslots. Contention based protocols CSMA and MMSN perform worse. MMSN performs worse than CSMA since some part of the timeslot is spent to listen on the broadcast frequency. In the single-hop scenario, having multiple-channels does not improve the results since senders transmit to the same sink node and have to wait for each other's transmission. When the topology is multi-hop and there is a single frequency (MHSF), transmissions of all the nodes interfere with each other. All the protocols perform quite bad. However, MC-LMAC still performs better since collisions are eliminated but it takes 6 timeslots to deliver all the data compared with the 4 timeslots in the single-hop scenario due to relaying of the messages. When there are multiple frequencies available (MHMF), MC-LMAC performs similar to the SHSF scenario achieving a performance very close to the maximum. On the other hand, MMSN performs better than the MHSF scenario but cannot achieve the throughput of the SHSF scenario.

If throughput is the issue, instead of using multiple-channels, using a more powerful radio with a higher data rate could work better than the multi-channel scenario. In the last column of Figure 2, we present the results where the nodes can transmit over a double size band, i.e. with an effective data rate of 500kbps. Compared with the results of MHSF and MHMF, all protocols achieve higher throughput. However, most of the band is still not utilized due to the interference experienced on the same channel. Additionally, using a radio that can transmit over a wider band consumes more energy which is not desired by WSN due to the limited battery on the sensor nodes.

Observations from the benchmark results are two-fold: Due to the common destination problem with the many-to-one traffic pattern, aggregate throughput is limited by the reception capacity of the sink node. However, this throughput is usually not achieved in multi-hop scenarios due to contention, interference and collisions that increase with relaying of data. Multi-channel communication can cope with interference and collisions and improve the throughput and delivery performance. Next, we conclude that schedule-based medium access can better cope with high peak loads [33] since the contention and collisions are eliminated.

IV. MC-LMAC PROTOCOL

MC-LMAC is a schedule-based multi-channel MAC protocol. The main design criteria are based on the single-channel LMAC [6] (lightweight medium access control) which is an energy-efficient medium access protocol designed for WSN. The LMAC protocol enables the communicating entities to access the wireless medium on a schedule basis in which each node periodically uses a timeslot to transmit. The main aspects of the protocol are: 1. *Self-configuration*: LMAC can operate in a fully-distributed, adhoc manner and does not require a central scheduler, 2. *Energy-efficiency*: Time-scheduling method has the natural advantage of collision free medium access, which avoids wasting energy.

Moreover, time-scheduled communication eases the coordination of multi-channel communication. Since nodes switch their interfaces between different channels, a detailed coordination of channel switching is required between the senders and receivers in order to be on the same channel at the same time. Scheduled access overcomes this complexity.

Another key aspect of the time-slotted communication is the robustness against high peak loads [33]. Alternative carrier-sense protocols may fail to successfully allocate the medium and result in collisions when the number of sources or the source rates increase. On the other hand, scheduled communication has the advantage of collision-free access. Since we focus on the scenarios with a high demand on the medium, we consider LMAC as the most optimal choice. In the following, we explain the properties of the timeslot assignment and medium access and how we extend the LMAC protocol to a multi-channel domain.

A. Timeslot and Channel Selection

In this section we present the localized scheduling algorithm of LMAC that allows nodes to (autonomously) choose a timeslot, such that it does not interfere the communication between other nodes in the network.

Each node gets periodically a time interval, called a timeslot, during which it is allowed to control the wireless medium and transmit its data. Timeslots are organized into frames. If there is no conflict (we explain the causes and resolution of conflicts in Section IV-A1) the node uses the same timeslot in the upcoming frames. Each frame has a fixed number of timeslots (required number of timeslots depends on the density of the deployment). Due to the multi-hop nature of WSN, the re-use of timeslots is possible. We assume all the nodes control one timeslot per frame but the algorithm can be extended to allocate more timeslots, i.e. allocate more rate, if needed [34]. Nodes are notified when they are intended receivers and if they are not addressed, they can turn off their transceivers to save energy.

When a node joins a network, first it has to discover a "free" timeslot to transmit its data. A free slot is defined as a slot:

- which is not used by direct neighbors of the node: in the opposite case, a node would not be able to exchange messages with those neighbors.
- which is not used by the nodes whose transmissions may get interfered or may cause interference with the transmissions of this node.

To guarantee that the first constraint holds, a node that is searching for a free timeslot should exclude all timeslots during which a message is received (or a carrier is detected) from the list of potential slots. The other constraint should be fulfilled by the potential receivers such that they should transmit a list of the timeslots during which they are already receiving (or detecting a carrier). This lets the new node to determine the list of free slots that can be used without interfering other transmissions. With this information, the nodes get a view about the timeslot usage in their 2-hop neighborhood and make a list of potential free slots. We assume a node randomly selects its timeslot from the set of free slots (for other methods of timeslot selection the reader can refer to [6]).

Timeslot selection is implemented as follows: All the nodes keep a bit vector called "occupied slots vector" with a length equal to the number of timeslots. It is used for storing the information about the slots occupied by the neighbors and the vector is transmitted during the node's timeslot to share this information for potential transmitters. Initially it's filled with 0's, meaning all the slots are free. When a packet is received or a carrier is detected during a timeslot, the node inserts a "1" in the vector at the respective position of the timeslot. To get a 2-hop view of the network, a node is required to collect transmitted bit vectors. After a complete frame has passed, the node can make a list of the free slots by executing an 'OR' operation on all the received occupied slots vectors and the local occupied slots vector.

The number of required timeslots per frame depends on the connectivity of the network topology. If the number of timeslots is larger than what is required, the bandwidth may get wasted during empty slots and nodes have to wait longer before they can access the medium. On the other hand, when there are not enough slots (i.e. the local connectivity is higher than expected), the node remains in initialization state, periodically monitoring frames for an empty timeslot. In single-channel LMAC, the number of transmissions is limited by the number of timeslots in a frame. However, in MC-LMAC timeslots are selected with frequencies. A node can use the same timeslot that is used by a 2-hop neighbor on a different frequency so that parallel transmissions are not disturbed at the common neighbors. Consequently, more transmissions can take place with the same number of timeslots.

In MC-LMAC, nodes keep occupied slots vectors per channel and select a timeslot to be used on a particular channel. A node which is trying to get the control of a timeslot, executes the "OR" operation over each occupied slots vector per channel and discovers the free slots on different channels. Similar to single channel LMAC, this method guarantees that the same "timeslot/channel" pair is not used in the 2-hop neighborhood. Note that the nodes do not select the timeslots used by their direct neighbors on any frequency due to the limitation of the half-duplex radio.

Figure 3 shows an example for timeslot and channel selection. The node marked with "?" is searching for a timeslot and other nodes are marked by timeslot/frequency pair that they are using. The number of timeslots per frame is 5 and the number of frequencies is 2. The node without a timeslot receives the occupied slots information (the position of a bit in the vector is the timeslot number: 1 means the timeslot is occupied and 0 means free) from the neighbors, executes the OR operation and finds that all the slots are occupied on F1 (frequency 1), however there are free slots on F2. The node selects timeslot 5 (which is not occupied by the direct neighbors) on F2.

1) Conflict Resolution: Nodes always use the same timeslot periodically in each frame unless a collision occurs. Collisions can occur when two or more nodes choose the same timeslot

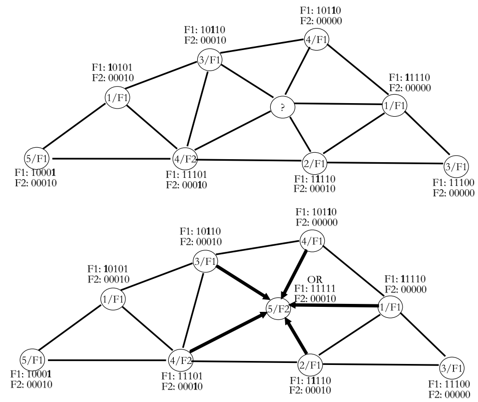

Fig. 3. MC-LMAC timeslot and channel selection

to control. This can happen during network setup or when network topology changes due to for instance variations in link quality. When a collision has been detected at a timeslot, the node records the number of the timeslot and reports this during its own timeslot. If the reported number matches with the timeslot of a node, the node releases its timeslot and restarts the timeslot selection procedure. To reduce the number of collisions especially at the start up, nodes wait random times to start with the timeslot selection.

2) Time Synchronization: Multi-hop time synchronization is achieved by a hierarchical scheme such that every node synchronizes with its parent (every node selects a parent node from the set of the nodes which are closer to the sink node in terms of number of hops). Synchronization details can be found in [6] and are outside of the scope of this paper.

B. Medium Access

As we mentioned, nodes transmit information during their timeslots. A timeslot consists of a control message (CM) period and a data transmission (DATA) period. The DATA section has a fixed maximum length. Depending on the amount of data the node can send only a single packet or multiple packets or the DATA section can be omitted.

In the CM period, nodes transmit control information prior to the data transmission. It is comparable to a beacon message in IEEE 802.15.4 MAC specification, and it provides collision-free addressing, maintaining synchronization and neighbor discovery. The contents of the control message transmitted during CM period and they are as follows: *ID* represents the node id of the sender, *Destination ID* is the receiver's id or it can be a broadcast address. *Occupied Slots* represents the bit vector for the occupied slots in the neighborhood, which was explained in Section IV-A. *Collision in Slot* represents the slot number during which a collision has been detected. *Current Slot* represents the slot number and it is used for synchronization by the new joining nodes. *Hops to Gateway* field lets the nodes announce their hop distance to the sink node and it is used for synchronization. *Acknowledgement bit vector* has a length equal to the number of timeslots per frame. Nodes keep track of the slots during which they receive data.

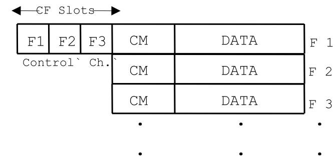

Fig. 4. MC-LMAC Timeslot structure

Initially the vector is filled with 0's. If a message is received, a logical 1 is inserted at the position of the respective timeslot in the acknowledgement field.

To support multi-channel communication, nodes select a timeslot together with a channel. Parallel data transmissions take place on the selected frequencies but the receivers are notified on the common frequency first. The timeslot structure of LMAC is extended as presented in Figure 4 in MC-LMAC by adding a common frequency (CF) period. During CF period, only the intended destination ID is transmitted. This enables the sender to notify the destination and invite the destination to switch its radio on the sender's channel.

Communication during CF period is also based on scheduled access and takes place on small slots called CF slots. The number of CF slots is equal to the number of channels and each slot is indexed by a channel number. A sender controlling the current timeslot addresses the destination during the CF slot which is reserved for the channel number it controls.

Receivers listen during the whole CF period in order to be informed about the intended destinations. If a receiver is addressed during a CF slot it switches its transceiver on the sender's associated frequency. If not, the node switches its transceiver to standby for the remainder of the timeslot to conserve energy. Note that the common frequency can also be used by the nodes for data transmission and it has the same characteristics as the other channels.

After the CF period the receiver switches on the sender's channel and the timeslot owner transmits CM, followed by the DATA section. Contents of the CM are the same as the single channel LMAC with the exception of the *Destination id*. The occupied slots vector includes information per channel and *Collision in frequency* field is added to distinguish the channel on which a collision has been detected.

An example of the overall medium access coordination is shown in Figure 5. The initial part shows the topology: the numbers inside the circles represent the id's of the nodes. It is assumed that there are 3 channels available (represented as $F1$, $F2$ and $F3$) and accordingly there are 3 CF slots. Sender 1 addresses node 4 on the first CF slot to communicate on channel $F1$, sender 2 addresses node 5 on the second CF slot to communicate on $F2$ and sender 3 addresses node 6 on the third CF slot to communicate on $F3$. CF section takes place on the control channel which is $F1$. In the CM and data sections, the nodes tune their transceivers on the associated channels: node 1 and 4 on $F1$, node 2 and 5 on $F2$, node 3 and 6 on $F3$. Note that, due to interference these three parallel transmissions would not be possible if there was only a single

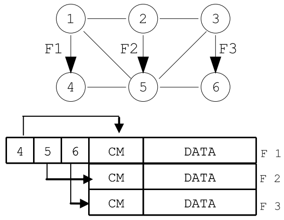

Fig. 5. MC-LMAC coordination scheme

channel available.

C. Discussion

An issue to be solved is about the receiver reaction if it's addressed by multiple senders in the same timeslot on different channels. We define this situation as a clash. An option would be to select a sender randomly or select a sender according to a priority mechanism. In the simulations, we use a priority mechanism during timeslot selection by prioritizing the selection of the timeslots that are not used by the other children of the parent node on the convergecast tree. This efficiently reduces the possibility of the clashes. To inform the unselected senders in the case of a clash, the acknowledgement field in the CM is used.

Another issue is the overhead of CF period added to the beginning of each timeslot. We try to keep this period as small as possible where the nodes transmit only the destination id. The overhead is compensated by allowing the transmission of multiple data packets during DATA section. In Section V we show that the CF period does not bring an overhead in terms of energy consumption compared with other protocols but it provides higher throughput at the sink node by coordinating transmission over different channels.

V. Performance Analysis

In this section, we analyze the performance of the MC-LMAC protocol by extensive simulations on Glomosim [8]. Different simulation scenarios are studied according to four different performance metrics: aggregate throughput, delivery ratio, latency and energy efficiency. Aggregate throughput is calculated as the total amount of data delivered to the sink node per unit time by the MAC protocol.

We study the performance according to different system loads, different source rates, different number of frequencies, different node densities and different traffic patterns. Simulation parameters are presented in Table II. We use the RADIO_ACCNOISE model, which simulates the behavior of the physical interference model [35] such that interference from multiple senders is captured. According to the radio parameters the transmission range of the nodes is around 40m. The sink node is positioned in the center of a square area. In most of the simulations, the Geographic Forwarding (GF) [36] routing protocol is used but we also study the performance of a gossip traffic pattern without GF.

Performance of MC-LMAC is compared with MMSN which was discussed in Section II-B2. Moreover, we simulated a previously introduced channel assignment algorithm [37] where each branch of the convergecast tree is assigned a different channel, in other words each branch is clustered into different channels. Inside the clusters nodes communicate according to the single-channel LMAC protocol and we refer to this as clustered LMAC. The operation of clustered LMAC is similar to TMCP [28] which was mentioned in Section II-B2. In TMCP the level of interference that a node creates on the nodes of a branch is considered. However, in MC-LMAC, nodes join the branches according to the minimum hop count to the sink node or randomly in case of a tie. We also compare the performance of MC-LMAC with clustered LMAC and CSMA. All the results are averaged over 1000 simulation runs.

Terrain Size	150*150 m^2
Number of Nodes	100
Node Placement	Random
Number of Frequencies	1 - 10
Bandwidth	250kbps
Transmit Power	1dBm
Radio Model	RADIO_ACCNOISE
Radio Range	40m
MAC Protocol	MC-LMAC, MMSN
Routing Protocol	GF

TABLE II
Simulation Parameters

A. Impact of the Number of Channels

In this section we analyze the impact of the number of channels on the network performance. All the nodes initiate CBR streams towards the sink node and each node generates a packet in every 2 seconds (if nodes transmit more frequently, buffer overflows start to occur). The number of channels is varied between 1 and 10. The terrain size is 150*150m^2.

Figure 6 presents the results in terms of aggregate throughput. The x-axis shows the number of available channels whereas the y-axis shows the aggregate throughput in terms of the number of bytes per second received by the sink node. Maximum aggregate throughput at the sink node is 1584 bytes/sec (99 sources generate 32 byte packets every 2 second). Different lines present the results collected with different protocols: MC-LMAC, MMSN, Clustered LMAC and CSMA. In MC-LMAC, the number of timeslots per frame is 32 (adapted according to the expected network node density) and each timeslot is approximately 50msec long. This allows the nodes to transmit multiple packets (on the average 15 per time slot). In contrast, a timeslot in MMSN is only long enough to send one broadcast packet and one data packet.

Aggregate throughput increases when the number of channels increases from 1 to 10 (although the example radios such as Nordic Nrf905 provides more channels, the number of orthogonal channels is rather limited) with all the protocols except CSMA where the number of channels is fixed to 1. MC-LMAC achieves lower throughput than MMSN with 1-3 frequencies since some of the nodes cannot get a free timeslot and cannot start transmissions. As the number of channels increases, more nodes can control a timeslot. After 6 channels, MC-LMAC performs very close to the maximum throughput, and with 8 or more channels, the maximum throughput can be

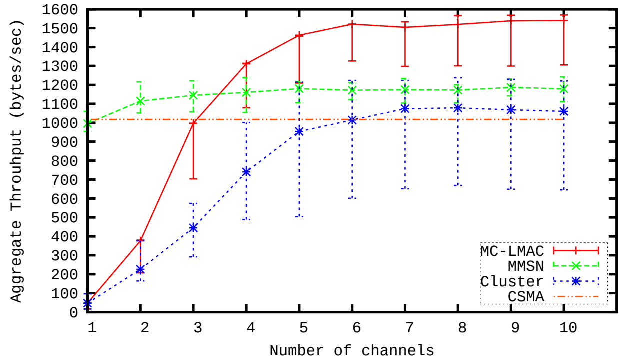

Fig. 6. Aggregate throughput with different number of channels

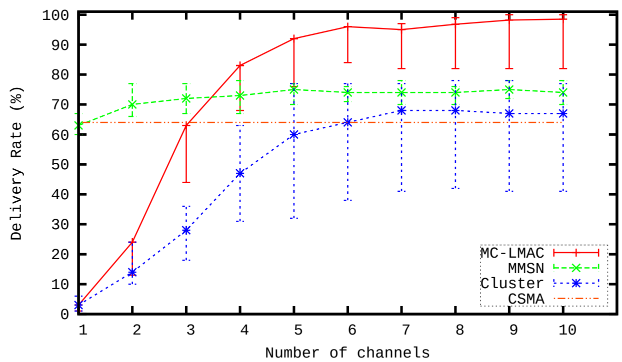

Fig. 7. Packet delivery rate with different number of channels

achieved. On the average, the achievable throughput is 99% of the maximum throughput. %1 loss is due to the clashes that may occur. In the implementation of the protocol we reduced the possibility of the clashes by prioritizing the selection of the timeslots that are not used by the other children of the parent node on the convergecast tree.

Aggregate throughput with MMSN is observed to be limited and does not increase after 6 channels. This is due to the failure of the nodes around the sink to successfully sense the channel and prevent the collisions. Achievable throughput with clustered LMAC is rather limited due to the single-channel communication inside the clusters. Nodes need to select timeslots that are not used in the 2-hop neighborhood to prevent collisions and interference. On the average, single channel CSMA achieves an aggregate throughput of 64% of the maximum throughput. Due to the high contention, the protocol fails to successfully allocate the medium to the nodes. Compared with CSMA, MMSN achieves slightly lower throughput with a single channel which is due to the time spent on sampling the broadcast channel at the beginning of each slot.

Figure 7 presents the results in terms of delivery ratio. The x-axis shows the number of available channels whereas the y-axis shows the delivery ratios. The figure has a very similar shape with the aggregate throughput graph presented in Figure 6. With sufficient channels, MC-LMAC achieves to deliver on the average 99% of the packets. As we mentioned, the small percentage of losses is due to the clashes. However, with a smaller number of channels, the delivery ratio is rather limited since most of the nodes cannot get a free timeslot. On the other hand, contention based MMSN protocol saturates around 70% delivery ratio with the increasing number of channels and CSMA delivers only 64% of the packets.

Figure 8 shows the results in terms of end-to-end latency between the transmission of a packet at the source node and reception at the sink node. Although MC-LMAC achieves lower latency than clustered LMAC and CSMA, MMSN has much lower delay compared with the MC-LMAC protocol. Higher latency is a typical characteristic of the schedule-based protocols. If a node has a packet to transmit it has to wait till its assigned slot. The average delay from source to the sink is equal to a frame size which is approximately 1.6 seconds (the selection of the timeslots that are before the parent node's slot are prioritized). A simple solution to decrease the latency would then be to decrease the frame size. However, in that case the number of packets that can be delivered per timeslot will also decrease and the packets will be buffered to be transmitted later. The best option is then to assign the relaying nodes consecutive timeslots according to their hop distance to the sink node. We previously explored the performance gains with this method in [38]. CSMA also experiences higher delay than MMSN which is due to the exponential and higher number of backoffs due to the high contention. In contrast, MMSN uses a different backoff algorithm.

Figure 9 shows the results in terms of energy-efficiency per successfully delivered packet. We consider both the energy spent to receive and transmit as well as the energy spent for relaying the packet towards the sink node. Energy spent per delivered packet is quite high with MC-LMAC when there is only a single channel. This is due to the very low delivery rate. As the number of channels increases, both MC-LMAC and MMSN spend much less energy than CSMA. MC-LMAC can provide higher throughput while meeting the energy efficiency constraint of WSN.

B. Impact of Load

In this section, we analyze the impact of the load on the network performance. In particular we vary the number of

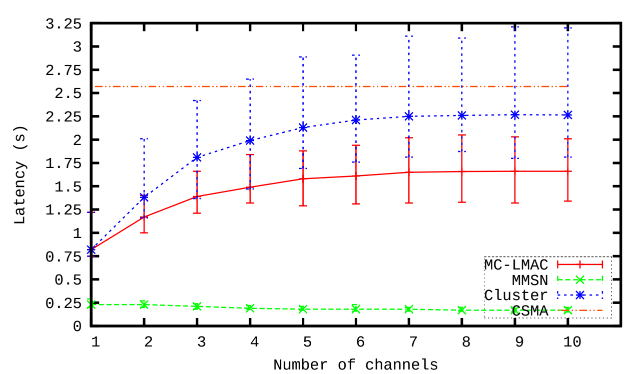

Fig. 8. Latency with different number of channels

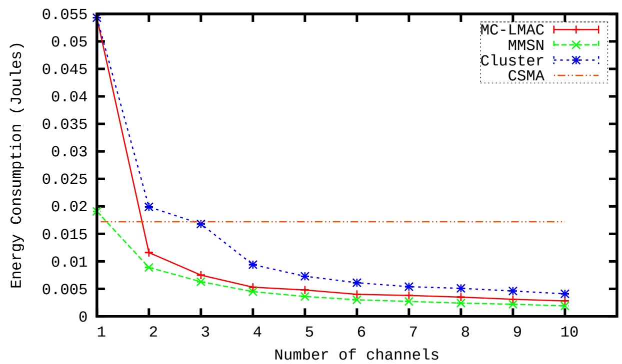

Fig. 9. Energy consumption with different number of channels

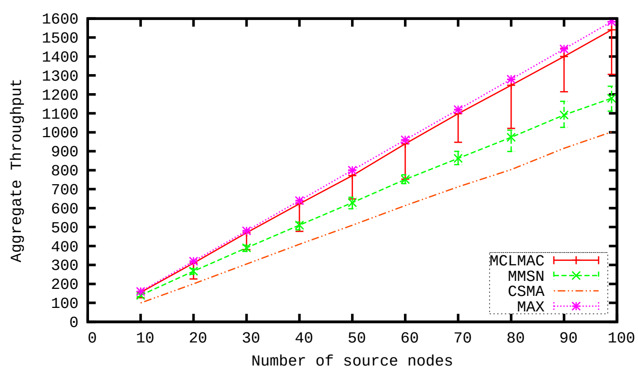

Fig. 10. Aggregate throughput with different number of sources

sources. The aim is to investigate the performance of the protocols with different levels of contention.

Figure 10 shows the results in terms of the active sources. We vary the number of sources from 10 to 100. The number of channels for both MC-LMAC and MMSN is 10. Since the MC-LMAC assigns slots to all of the nodes, whether they are the sources or not, the performance of MC-LMAC is close to the maximum aggregate throughput in all cases. However, MMSN and CSMA suffer from contention. When more sources are active, the contention mechanism cannot sense the incoming packets at the destination's frequency with MMSN particularly around the sink node.

In this set of simulations, the nodes generate packets in every 2 seconds. We also investigated scenarios where nodes generate packets more frequently. We cannot present the results here due to the limited space but all the protocols experience buffer overflows with higher data rates and the achievable throughput gets much lower than the maximum.

C. Impact of Density

In this section, we evaluate the impact of density on the performance of the protocols to test the scalability. We vary the terrain size between $50{*}50m^2$ and $225{*}225m^2$ (beyond 225m, unconnected nodes appear). Figure 11 presents the results. The x-axis shows L, the side length of the deployment area whereas y-axis shows the aggregate throughput. The number of channels is 10 for both MMSN and CSMA. Aggregate throughput with MC-LMAC is lower when $L \neq 150$ since 32 slots per frame is lower in denser scenarios and higher in sparser scenarios than required. During unused timeslots in sparser scenarios the sink stays idle. We repeat the experiments with different numbers of timeslots that are adjusted according to the expected connectivity and the results are presented with the second line where the maximum throughput is achieved. Aggregate throughput with MMSN continues to increase when the network gets sparser since the contention is lower and the nodes can successfully sense the incoming packets. However, the performance of MMSN is still lower than MC-LMAC.

D. Impact of Traffic Patterns

In this section we evaluate the network performance with a different traffic pattern: local gossip. We can think of this scenario as in-network processing such that the source nodes exchange packets before they decide to transmit the data towards the sink node. The nodes in the center of the terrain are assumed to be the sources and they exchange broadcast packets.

We assume a $30{*}30m^2$ (such that all nodes are within the transmission range of each other) area where the source nodes are located. We vary the density by changing the terrain size and the number of channels is 10 for MC-LMAC and MMSN. Figure 12 shows the results in terms of delivery ratios. When the network is dense, the rate of successful deliveries is low. MC-LMAC suffers from the clashes whereas CSMA and MMSN suffer from collisions. Additionally, the number of timeslots with MC-LMAC is 32 which causes some of the source nodes not to be able to get a slot. In order to achieve higher deliver ratios in denser deployments, the number of timeslots should be increased as we discussed in Section V-C. When $L \geq 125$ MC-LMAC can deliver more than 98% of the broadcast packets. In contrast, MMSN and CSMA protocols need more sparseness to mitigate the effects of contention.

E. Multiple Sinks with a Single Channel versus a Single Sink with Multiple Channels

As we discussed in Section III, the limiting factor is the reception capacity of the sink node. Contention based protocols fail to successfully allocate the medium during high contention

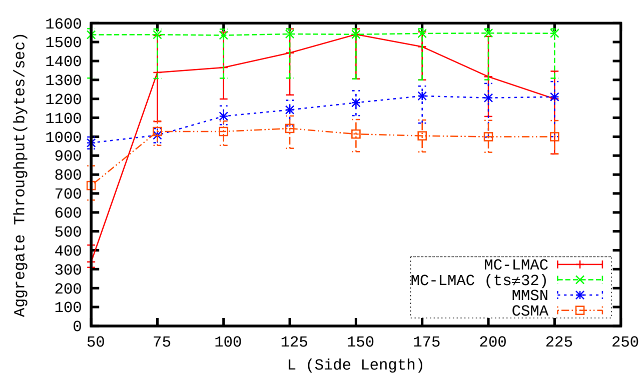

Fig. 11. Aggregate throughput with different densities

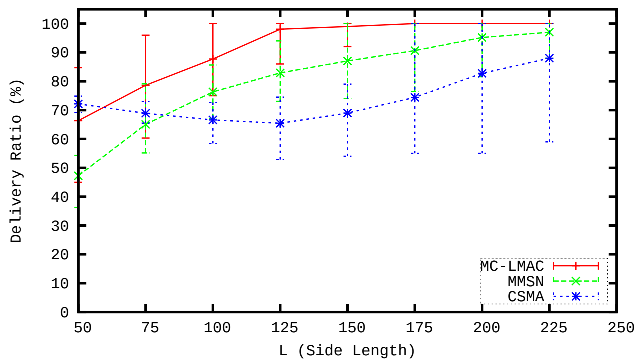

Fig. 12. Delivery Ratio with different densities

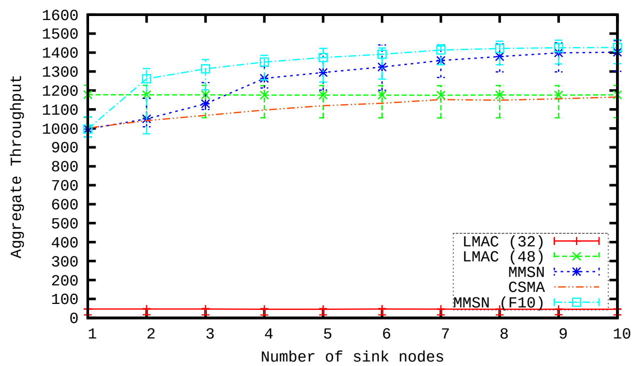

Fig. 13. Aggregate throughput with different number of sink nodes

around a single sink node. In this section, as an alternative to single-sink multi-channel scenario, we discuss the impact of deploying more sink nodes using a single-channel on the achievable throughput.

Multiple sink nodes are randomly deployed in the area. Source nodes transmit packets in every 2 seconds to the closest sink node. Figure 13 shows the results. In this set, the nodes communicate on a single channel (except the line titled "MMSN (F10)" in the figure). Our aim is to compare the results of n sink nodes with 1 channel with the results of 1 sink node with n channels which were presented in Figure 6. Compared with the results in Figure 6, both CSMA and MMSN achieve higher throughput since the contention around the sink nodes has lower impact compared with the contention around a single sink. Beyond 4 sink nodes, MMSN starts to perform better than MMSN with 4 channels and a single sink node. However, around 9 sink nodes the aggregate throughput starts to saturate.

In contrast, the single channel LMAC has a constant lower performance with a single channel and 32 timeslots since most of the nodes cannot get a free slot on a single channel. However, if the number of timeslots is increased to 48, a higher performance is achieved. Although the packet delivery ratio with 48 timeslots is 100%, the aggregate throughput is on the average 75% of the maximum aggregate throughput since the nodes cannot choose the timeslots that are used by their 2^{nd} hop neighbors on the same channel and this reduces the number of parallel transmissions. Compared with the results in Figure 6, MMSN and CSMA perform better with multiple sinks but still they cannot achieve the performance of MC-LMAC with multiple channels which has the advantage of collision free medium access over multiple channels.

The line named "MMSN (F10)" in the figure shows the results when MMSN operates with multiple sink nodes and there are 10 channels available. The performance is better with 10 channels for a smaller number of sink nodes than single channel communication results given on the line titled "MMSN". However, beyond 7 sinks there is little difference in the performance and aggregate throughput is still less than the achievable throughput with MC-LMAC where there is a single sink to collect data over multiple channels (Figure 6). Multiple sink nodes can be used as a complementary for MC-LMAC that can further improve the achievable throughput for higher data rate scenarios.

F. Implementation on Sensor Nodes

The single channel LMAC protocol has been implemented and previously tested [6] on Ambient μNode sensor platform. We added the MC-LMAC extension and performed a simple test as a proof of concept using a simple topology where 2 pairs of nodes are communicating in parallel. The aim of the experiments is to investigate the impact of channel switching on the synchronization of the nodes.

The sensor platform is equipped with Nordic Nrf905 radio that can operate on the 868/915 MHz ISM band. Channel switching time is around $650\mu sec$. Nodes continuously transmit 32-byte packets every 1/8 second. The results cannot be presented due to the limited space but the conclusion of the experiments is that nodes can change their operating frequency without loosing the synchronization. The aggregate throughput with parallel communication over different channels is doubled, as expected.

As a future work, we are interested in comparing the performance of different protocols on real sensor nodes on a larger testbed.

VI. Conclusions

We have presented MC-LMAC, designed for wireless sensor networks with high throughput requirements. MC-LMAC takes the advantage of both scheduled and multi-channel communication. Scheduled communication has the advantage of minimizing collisions whereas the multi-channel communication overcomes the increased contention and interference on the limited bandwidth and improves the throughput and bandwidth utilization. Nodes can transmit in parallel on different channels without disturbing each other.

Simulation results show that, MC-LMAC achieves a throughput very close to the maximum with the increased number of channels and outperforms the MMSN protocol and the channel clustering method for moderate-size, 100-node networks. While MC-LMAC supports higher throughput, it also meets the typical characteristics of WSN such as energy efficiency and scalability. Besides convergecast traffic MC-LMAC supports broadcasts and local gossip operations are performed efficiently. As a proof of concept, a simple test case of MC-LMAC demonstrates that nodes do not loose synchronization while switching between frequencies.

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