PMCMTP's implementation (in nesC/TinyOS2.x) and Testbed for its operation validation

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***Abstract*—PMCMTP is a Prioritized Multi-Channel Multi-Time slot MAC protocol that the authors have proposed for allowing to simultaneous use of several frequency channels. This protocol is designed for UWB of IEEE802.15.4a but it can also be used over IEEE802.15.4. In this paper, we design and implement a testbed of this protocol to demonstrate its practical implementability. Due to the unavailability of UWB transceiver, the testbed has been realized using classic 2.4GHz WSN transceivers. To reduce the complexity of resource sharing, the global network is composed of a set of Personal Area Networks (PANs) or cells. So, the PMCMTPs experiments are realized for a single PAN and two PANs. Also, a simulation is performed to evaluate the performance of the network under the PMCMTP process.**

***Keywords*-WSN; PMCMTP; Testbed.**

I. INTRODUCTION

Wireless sensor networks may consist of a collection of spatially distributed autonomous sensor nodes characterized by limited memory, processing capability and battery power supply. Such networks represent an emerging technology with wide range of potential applications such as medical systems, environment monitoring, military applications, etc. An important fact that can not be neglected in WSNs is the need of quality-of-service (QoS) support. According to novel application requirements, QoS constraints become more and more critical in terms of end-to-end delay and data throughput. Also, due to energetic constraints at node level, energy saving remains the most challenging issue. Both IEEE 802.15.4 and its recent amendment IEEE 802.15.4a [1] standards allow dynamic channel allocation and use of multiple channels available at their physical layers but their MAC protocols are designed only for single channel. Also, sensor's transceivers such as CC2420 used by current WSN hardware (MICAZ, TelosB, and CMU FireFly), provide multiple channels, and as shown in [2] and [3], channel switch latency of CC2420 transceiver is short (just about $200\mu s$). So this gives the possibility to simultaneous use of multi-channels, greatly increasing data throughput. However, in the general case of dense Mesh WSNs, the exploitation of the multi-channel access is complex. This explains the imperative need to propose an adequate network architecture that can simplify and reduce the complexity of the resource sharing task in such networks and to design a scalable and optimal multi-frequency MAC protocols. Most currently deployed sensor networks use the same channel to communicate information towards nodes. This is a source of great inefficiency as it poorly utilizes the available wireless spectrum. In this context, we have proposed in [4] PMCMTP, a Prioritized Multi-Channel Multi-Time slot media access control Protocol for dense and large-scale WSNs to ensure an efficient resource allocation, in terms of channel frequencies and time slots inside each PAN, obeying to QoS constraints (i.e., priority of resource requests). The PMCMTP takes into account the spatial channel reuse, the duty cycle's information of PANs and the support of data stream prioritization.

The WSNs research is currently gaining an exponentially increasing interest from both academia and industry. New application scenarios, MAC, routing and physical layer optimizing protocols and algorithms are being developed by the research community. The ultimate test for the validity of these research activities is to implement the various scenarios, algorithms and protocols on a testbed and deploy it in a realistic setting. In this paper, we present, and implement a practical Multi-channel Multi-Time slots MAC Protocol for WSNs. We, experimentally, validate the proposed MAC protocol by using a realistic testbed setting and evaluate its performance by simulation.

II. RELATED WORK

The idea of multi-channel MAC protocols is not new in the wireless network research community. Recently some MAC layer multi-channel protocols have been proposed to improve network performance in WSNs. The first multi-channel protocol, called Multi-frequency Media access control for wireless Sensor Networks (MMSN) [5], represents four frequency assignment schemes for WSN: exclusive frequency assignment, even selection, eavesdropping and implicit-consensus. Although MMSN achieves increased network throughput, the fixed channel allocations limit channel utilization. Moreover, it wastes a lot of energy due to several broadcasts and collisions. Y-MAC [6] is a TDMA-based multi-channel MAC protocol for WSN. Y-MAC, based on scheduled access, assigns time slots to the receivers instead of the senders. At the beginning of each time slot, potential senders for the same receiver contend for the medium. We note that increased contention especially around the sink node with high data-rate scenarios can lead to bottleneck problem of the sink node. In this situation, several packets can exceed the delay bound of the underlying application and it can be dropped. So, neither QoS constraints will be respected nor energy will be saved. To overcome the deficiency of single-channel LMAC protocol in dense networks, Multi-channel Lightweight Medium Access Control (MLMAC) [7] has been proposed. In single-channel LMAC, the number of transmissions is limited by the number of time slots in a frame. Although, MLMAC exhibits better performance than LMAC in terms of throughput due to parallel transmissions, energy saving is not improved. Also, collisions can occur when network topology changes which leads to energy wastage. In [8] and [9], the authors proposed a dynamic channel allocation based on agreement established between each sender and receiver nodes. Such approach may be suitable in light network but in dense network frequency negotiation messages can involve a considerable unnecessary overhead. The advantage of those protocols is the use of several channels for control traffic which can avoid control channel congestion problem. There are also efforts in industry which utilize multi-channel radios. Time Synchronized Mesh Protocol (TSMP) [10] is a TDMA-based frequency hopping networking protocol for wireless mesh sensor networks (WMSNs). TSMP maintains synchronization among nodes. Nodes employ frequency hopping according to a shared pseudo-random schedule. The authors in [11] proposed the first Multi-Channel MAC protocol (MCMAC) taking into account the notion of priority during channel allocation process inside a cluster. This protocol is based on four stages: synchronous beacon, transmission request, channel schedule and data convey. Although MCMAC ensures multi-channel access in cluster tree WSNs but it does not support the simultaneous communications of several clusters. Moreover, the cluster header assigns channels to its members for a fixed duration which leads to the wasting of resource (if this duration is bigger than needed duration) and\or to the increase of communication overhead (if this duration is shorter than needed duration). In [12], the authors proposed the first multi-channel scheme designed for UWB based IEEE 802.15.3 networks. Based on dynamic traffic demand, the proposed mechanism employs a distributed dynamic channel allocation algorithm to distribute the channels among neighboring piconets. Because of several broadcasts (between piconet controllers), the communication overhead in this mechanism is relatively high.

The majority of the proposed protocols were tested and evaluated by simulations, using personal or academic or commercial network simulator, where few of them were validated and evaluated by testbed deployed in a realistic setting.

Our paper makes the following main contributions:

- First, it proposes PMCMTP, a Prioritized Multi-Channel Multi-Time slot media access control Protocol for dense and large-scale WSNs to ensure an efficient resource allocation, in terms of channel frequencies and time slots inside each PAN, obeying to QoS constraints (i.e., priority of resource requests). The PMCMTP is implemented in the nesC [13] programming language for MicaZ [14] motes with TinyOS-2.x. [15]

- Second, we deployed a WSN testbed to ensure the experimental validation of the proposed protocol,

- Finally, using simulation, we perform an evaluation of our protocol, demonstrating that it comes to reach our goals in terms of network performance enhancement and spectrum efficiency.

The rest of the paper is organized as follows: In Section 3, we present the system model. Section 4 gives an overview of the PMCMTP protocol. Section 5 gives a brief overview of the implementation of the PMCMTP on the MicaZ motes. In Section 6, we validate and demonstrate the effective operation of the PMCMTP and evaluate its performance by analyzing and commenting some experimental and simulation results.

III. SYSTEM MODEL

We have proposed in [16] the WHSN (Wireless Hospital Sensor Network) for an application in hospital (medical monitoring of patients and management of doctors). The WHSN is a three-tiered network, using UWB sensors in the first and second network levels and WiFi technology for the third tier (See Figure 1). The different network tiers are as follows:

1) First tier or the BSN (Body Sensor Network): a star network composed of one coordinator and a set of biosensors that ensure physiological measurements and the medical monitoring of patient.
2) Second tier or the PAN (Personal Area Network): a hexagonal cell of sensors organized in a full mesh topology including one PAN's coordinator, several mobile BSNs coordinators (one coordinator per BSN) and several routers.
3) Third tier or the Cellular Mesh WiFi Network: based on UWB/Wifi technologies, is chosen to the third level to have finally a three-tier hierarchical cellular network.

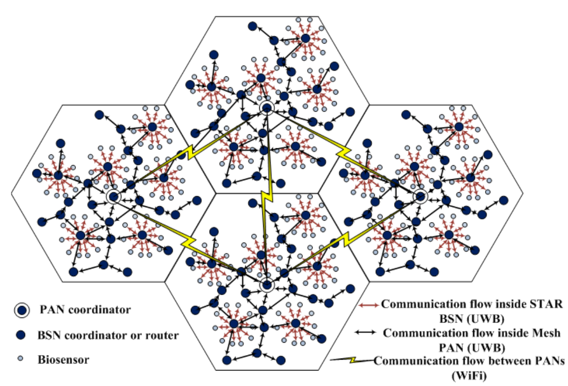


Fig. 1. Network architecture

The detailed description of the global network architecture is out of the scope of this paper, so for more details, one can refer to [16]. We focus in this paper to the second tier or the PAN. So, we consider a set of PANs organized on hexagonal cells to facilitate the spectrum resource allocation. Each PAN is composed by one coordinator and a set of router and/or source nodes. A source node can act as a BSN coordinator or a simple node. To provide time guarantee to deliver data frames, beacon-enabled mode is used. The format of the superframe is defined by the PAN Coordinator. The superframe, corresponding to the Beacon Interval (BI), is defined by the time between two consecutive beacons, and includes an active period and, optionally, a following inactive period. The active period, corresponding to the Superframe Duration (SD), is divided into 16 equally sized time slots, during which data transmission is allowed. For a global network of N_c PANs, each PAN coordinator is characterized by its superframe duration $\{PAN_i = (SD_i, BI_i)\}_{1 \leq i \leq N_c}$ as shown in Figure 2. We define $\overline{BI_{maj}}$ and $\overline{SD_{min}}$ as respectively the major cycle (the least common multiple of all PANs BI) and the elementary active cycle (the least common denominator of all PANs SD).

IV. PMCMTP FOR IR UWB SENSOR NETWORKS

In [17], we have proposed a channel allocation scheme to statically assign one control channel to each PAN to support the control traffic and dynamically share the set of available data channels between active PANs to support data traffic. The detailed description of the proposed channels (Control and data channels) sharing between PANs is out of the scope of this paper, so for more details, one can refer to [17]. So, let us assume that each PAN permanently dispose a control channel to ensure control traffic and a variable set of data channels to ensure data traffic. In this section, we focus on the detail of the PMCMTP [4] for logical channels and time slots allocation inside each active PAN. Similar to [18], a key concept in PMCMTP is the elementary active cycle, which is composed by two consecutive active periods, the first for synchronization and collection of resource requests, and the second for the Request Scheduling Algorithm (RSA) process, the reception of the second beacon and the allowable data communications (See Figure 3).

Inside each PAN, according to the PMCMTP, the PAN coordinator collects all the resource allocation requests of its sources nodes. Then, according to the available spectrum resource, it tries to allocate available time slots per available channel of frequencies in response to the collected requests. Finally, concerned sensors can start their data communication. The principle of PMCMTP is based on the three following phases:

1) *Synchronization and Request Transmission:* Transmission requests phase must precede each PAN's data communication active period. This phase is divided into two sub-steps :
(i) the first step consists in PAN synchronization: by listening to the beacon frame, PAN members adjust their wake-up clocks,
(ii) the second step consists in collecting all transmission requests from PAN's members. This step represents a set of equal short time slots, during which, the PAN coordinator is listening to the requests of PAN's member. So, just following the reception of the first beacon frame, each PAN's member waits for its own time slot in order to send its request packets. During this phase, the allocated control channel is used.
2) *Channels/time slots allocation :* According to the RSA algorithm, after reception of all transmission requests, the PAN coordinator tries to schedule them according to their assigned priority. Once the list of requests is scheduled, the PAN coordinator tries to launch the phase of time slots and channels allocation. For each request, it tries to find the earliest available time slots per channel to assign it to the suitable request. At the end of the process of time slots and channels allocation, the PAN coordinator registers a trace of the requests not served in its queue in order to analyze them during the next cycle. Then, it inserts into the next beacon frame the necessary information (Request identifier, index of allocated channel, index of the first allocated time slot, number of allocated time slots, address of the request's sender and of flow destination) of the served requests.
3) *Data communication:* After listening to the second beacon frame, PAN's members can have a feedback of their transmission requests. Each concerned sensor switches to the suitable channel at the suitable time slot and begins sending or receiving data frames during the reserved duration.

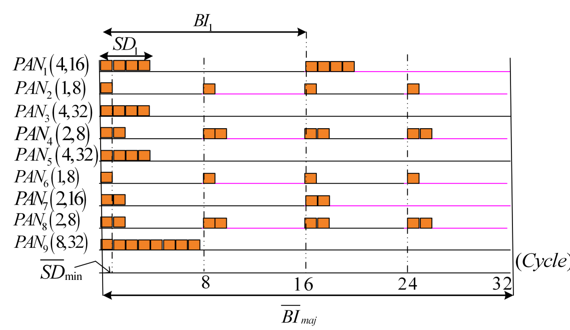


Fig. 2. Network configuration

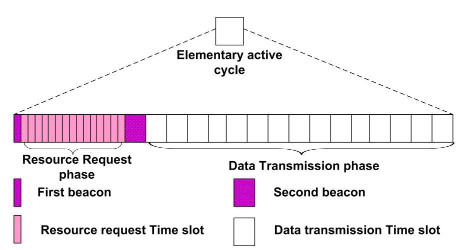


Fig. 3. An elementary active cycle

Figure 4 gives an example of a network using PMCMTP whose detail will be explained in the next section.

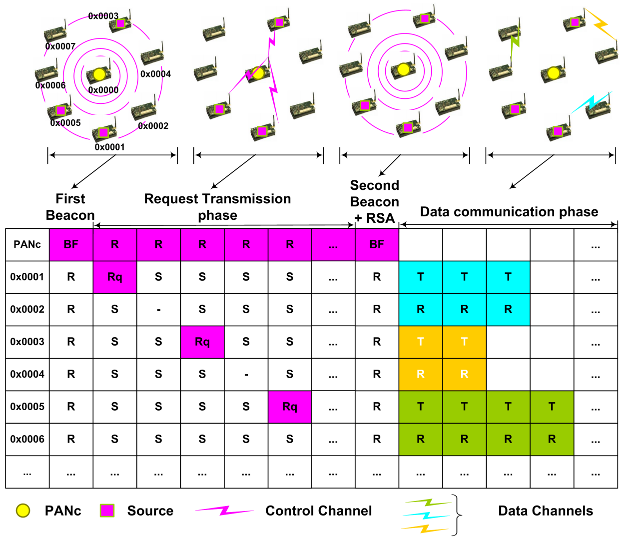


Fig. 4. PMCMTP process during an elementary active cycle

V. IMPLEMENTATION OF PMCMTP IN NESC/TINYOS2.X

Communication protocols and techniques are often tested and evaluated using simulation techniques. However, the use of realistic testbed setting for verification and evaluation in particular for WSNs becomes a necessity. In this part, we focus on the PMCMTP implementation in the nesC programming language for MICAz motes with TinyOS-2.x for the use in a real-world testbed setting to justify its operation validity in a real environment. The hardware used for the implementation of the PMCMTP protocol is the Crossbow MICAz motes, operating in the 2.4 GHz ISM band. The MIB510 [19] programming board was used to program the motes. The PMCMTP's implementation is composed of two components $CoordiatorC$ and $DeviceC$ respectively implemented at the coordinator and device motes and an interface $PMCMTP$.

A. Component CoordinatorC

The component *CoordinatorC* implements, for the coordinator mote, the MAC layer functions that will interact with upper and lower layers. This component ensures all tasks supported by the coordinator including the synchronization, the data sending, the reception of data and/or resource requests and all the treatment concerning the PMCMTP process. According to the Figure 5 illustrating the graph of the coordinator component, this component is implemented as a set of component modules written in nesC language. These components are connected to each other using adequate interfaces.

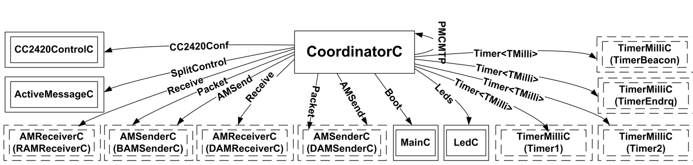


Fig. 5. Coordinator - Component Graph

B. Component DeviceC

The component *DeviceC* implements, for the device motes, the MAC layer functions that will interact with upper and lower layers. This component ensures all tasks supported by a device including the synchronization with the coordinator, the data and/or resource requests sending and the reception of data. According to the Figure 6 illustrating the graph of the Device component, this component is wired to other components of TinyOS library via the adequate interfaces.

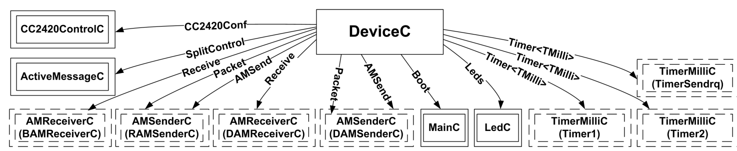


Fig. 6. Device - Component Graph

C. Interface PMCMTP

The interface PMCMTP defines required commands and hardware events to ensure the best execution of the RSA algorithm process. Given that the *CoordinatorC* uses and provides the interface PMCMTP it implements both hardware events and commands.

VI. VALIDATION OF PMCMTP OPERATION AND ITS SIMULATION EVALUATION

We have implemented the PMCMTP in both the Crossbow MICAz motes with the TinyOS environment to justify the validity of its operation process in realistic setting and on a discrete-time simulator, built in JAVA [20] and based on some functionalities defined by the Prowler simulator [21], for its evaluation via simulations. In this section, we propose to:

1) test the validity of the PMCMTP by realistic testbed setting,
2) evaluate its performance by simulations.

A. Experimental Testbed Operation Validation

A WSN testbed consists of a set of sensor nodes deployed in a controlled environment. It is designed to support experimental research in a real-world setting. It provides to researchers a way to test their protocols, algorithms, network issues and applications. For the testbed, a Sensor Network Analyzer SNA, consisting of a Jennic [22] mote, as hardware, and a laptop installing the SNA software is used. The SNA can be configured to scan a set of channel of frequencies by selecting the channels on which we want to perform the scan and its time duration. The functionality of channels scan, shows details of all devices detected using at least one of the selected channels over a specified period of time. For more details about devices and activity on a specific channel, we can select the channel on which we want to capture traffic. Two scenarios are driven to test the PMCMTP operation.

1) Test of the multi-channel access feasibility for a PAN composed by 5 motes: The scenario used to test the feasibility of PMCMTP operation is the following:

- The network is composed of one PAN coordinator and four devices as shown in Figure 7.

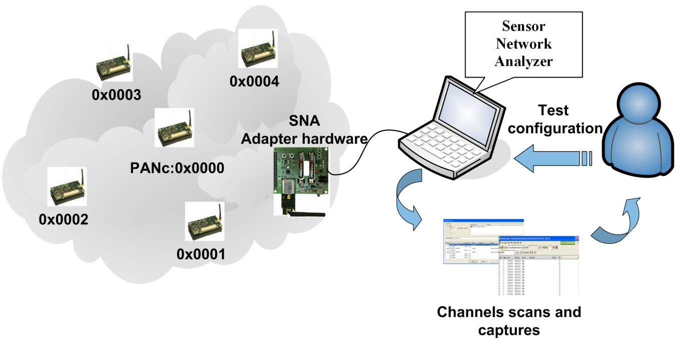


Fig. 7. Scenario 1

- The channel $N°26$ is allocated for control traffic (e.g., network synchronization and resource requests sending and reception).
- The channels $N°11$ and $N°15$ are allocated for data communication traffic.
- During the Request Transmission phase:
  - For the first time slot, Device (0x0001) sends, over channel $N°26$, to the coordinator a resource request to communicate with Device (0x0002),
  - For the third time slot, Device (0x0003) sends, over channel $N°26$, to the coordinator a resource request to communicate with Device (0x0004).

Experimental results

- Channels scan: We have launched a channel scan operation with a list of three channels ($N°11$, $N°15$ and $N°26$) and for a duration of 1 sec per channel.
  According to Figure 8 and Figure 9, we note that effectively:

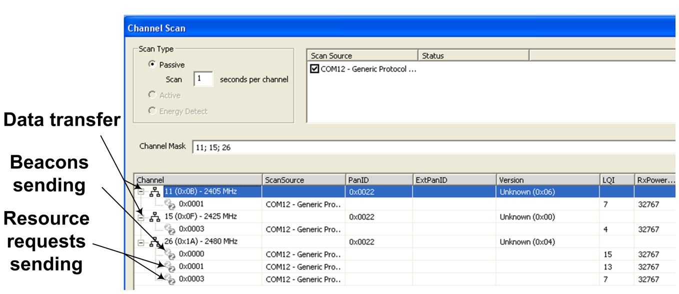


Fig. 8. Channels scan

∗ Channel $N°26$ is used by the coordinator to send beacon frames and by devices (0x0001 and 0x0003) to send their resource requests (See Figure 9(a));
∗ Channel $N°11$ is used by device (0x0001) to send data frames (Figure 9(b));
∗ Channel $N°15$ is used by device (0x0003) to send data frames (Figure 9(c));

Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	26	14:20:59.375		0x0000 First beacon →	Broadcast (0xffff)	IEEE 802.15.4	✓
2	26	14:20:59.381	+00:00:00.006	0x0001 First Resource Request	0x0000	IEEE 802.15.4	✓
3	26	14:20:59.412	+00:00:00.032	0x0003 Second Resource Request	0x0000	IEEE 802.15.4	✓
4	26	14:20:59.619	+00:00:00.207	0x0000 Second beacon →	Broadcast (0xffff)	IEEE 802.15.4	✓
5	26	14:20:59.866	+00:00:00.247	0x0000	Broadcast (0xffff)	IEEE 802.15.4	✓
6	26	14:20:59.872	+00:00:00.006	0x0001	0x0000	IEEE 802.15.4	✓
7	26	14:20:59.903	+00:00:00.031	0x0003	0x0000	IEEE 802.15.4	✓
8	26	14:21:00.113	+00:00:00.210	0x0000	Broadcast (0xffff)	IEEE 802.15.4	✓

(a) Scan of Control channel $N°$ 26

Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	11	15:38:38.170		0x0001	0x0002	IEEE 802.15.4	✓
2	11	15:38:38.171	+00:00:00.002	0x0001	0x0002	IEEE 802.15.4	✓
3	11	15:38:38.175	+00:00:00.004	0x0001	0x0002	IEEE 802.15.4	✓
4	11	15:38:38.178	+00:00:00.003	0x0001	0x0002	IEEE 802.15.4	✓
5	11	15:38:38.182	+00:00:00.004	0x0001	0x0002	IEEE 802.15.4	✓
6	11	15:38:38.185	+00:00:00.003	0x0001	0x0002	IEEE 802.15.4	✓

(b) Scan of Data channel $N°$ 11

Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	15	15:40:48.188		0x0003	0x0004	IEEE 802.15.4	✓
2	15	15:40:48.192	+00:00:00.004	0x0003	0x0004	IEEE 802.15.4	✓
3	15	15:40:48.195	+00:00:00.003	0x0003	0x0004	IEEE 802.15.4	✓
4	15	15:40:48.198	+00:00:00.003	0x0003	0x0004	IEEE 802.15.4	✓
5	15	15:40:48.201	+00:00:00.003	0x0003	0x0004	IEEE 802.15.4	✓
6	15	15:40:48.204	+00:00:00.003	0x0003	0x0004	IEEE 802.15.4	✓

(c) Scan of Data channel $N°$ 15

Fig. 9. Scan of channels $N°$ 26 , 11 and 15

- Packet timeline: By analyzing the scan of the control channel (i.e., channel N°26) over time, we can verify the control part of the PMCMTP process. According to Figure 10, we note that, using the channel $N°26$, periodically:
  - the PAN coordinator sends the first beacon to synchronize its network,
  - the source nodes according to their id, if they want, they can send a resource request to their coordinator to reserve resource (temporal and spectral resource according to demanded and available resource),
  - just before the end of the resource transmission phase, the PAN coordinator launches the RSA process to allocate resource in response to collected resource requests,
  - At the end of the resource transmission phase, the PAN coordinator sends the second beacon including the necessary information of served resource requests.

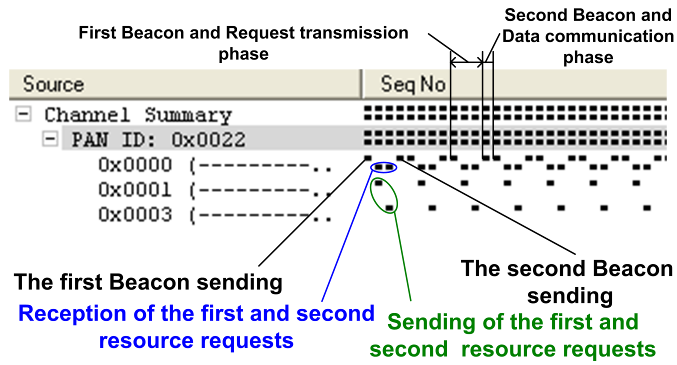


Fig. 10. Packet timeline over channel $N°$ 26

Compared to Figure 4, illustrating the principle of the PMCMTP operation, these results confirm the correct operation of the synchronization, the resource transmission phase and the data communication phase of the PMCMTP inside a PAN.

2) Test of the multi-channel access feasibility for two PANs of 5 motes each: To generalize the test of PM-CMTP operation validity for more than one PAN, we have used the following scenario:

- The network is composed of two PANs, and each is composed of one coordinator and four devices as shown in Figure 11.
- The channels $N°23$ and $N°26$ are respectively allocated to PAN1 (id=0x11) and PAN2 (id=0x22) to ensure control traffic.
- The set of channels $N°11$ and $N°17$ and the set of channels $N°14$ and 20 are respectively allocated to PAN1 and PAN2 to ensure data communication traffic.
- During the Request Transmission phase:
  - ∗ For the first time slot, Device (0x0001) of PAN1 (resp. of PAN2) sends, over channel $N°23$ (resp. $N°26$), to its PAN coordinator a resource request to communicate with Device (0x0002) of PAN1 (resp. of PAN2),
  - ∗ For the third time slot, Device (0x0003) of PAN1 (resp. of PAN2) sends, over channel $N°23$ (resp. $N°26$), to its PAN coordinator a resource request to communicate with Device (0x0004) of PAN1 (resp. of PAN2).

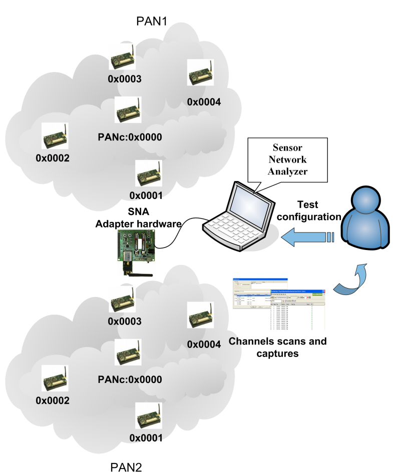
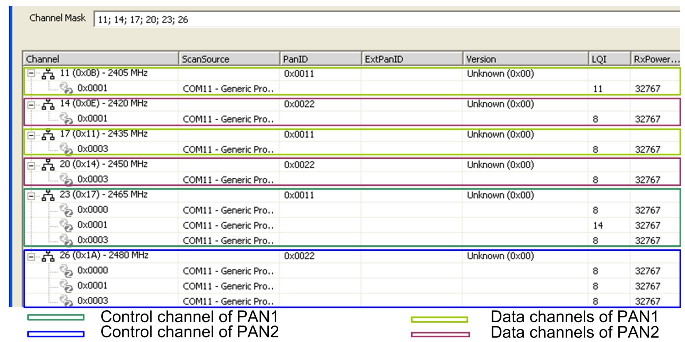


Fig. 11. Scenario 2

Experimental results

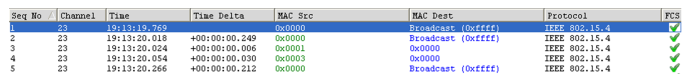
- Channel scan: We have launched a channel scan operation over six channels ($N°11$, $N°14$, $N°17$, $N°20$, $N°23$ and $N°26$) and for a duration of 1 sec per channel.
  According to the Figure 12, Figure 13 and Figure 14, we note that effectively:
  For PAN1 with PANid equals to 0x0011:
  ∗ Channel $N°23$ is used by the coordinator (0x0000) to send beacon frames and by devices (0x0001 and 0x0003) to send their resource requests;
  ∗ Channel $N°11$ is used by device (0x0001) to send data frames;
  ∗ Channel $N°17$ is used by device (0x0003) to send data frames;
  For PAN with PANid equals to 0x0022:
  ∗ Channel $N°26$ is used by the coordinator (0x0000) to send beacon frames and by devices (0x0001 and 0x0003) to send their resource requests;
  ∗ Channel $N°14$ is used by device (0x0001) to send data frames;
  ∗ Channel $N°20$ is used by device (0x0003) to send data frames;



Channel Mask: 11; 14; 17; 20; 23; 26

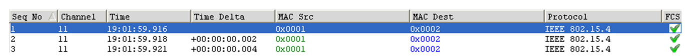
Channel	ScanSource	PanID	ExtPanID	Version	LQI	RxPower...
11 (0x0B) - 2405 MHz		0x0011		Unknown (0x00)		
0x0001	COM11 - Generic Pro..				11	32767
14 (0x0E) - 2420 MHz		0x0022		Unknown (0x00)		
0x0001	COM11 - Generic Pro..				8	32767
17 (0x11) - 2435 MHz		0x0011		Unknown (0x00)		
0x0003	COM11 - Generic Pro..				8	32767
20 (0x14) - 2450 MHz		0x0022		Unknown (0x00)		
0x0003	COM11 - Generic Pro..				8	32767
23 (0x17) - 2465 MHz		0x0011		Unknown (0x00)		
0x0000	COM11 - Generic Pro..				8	32767
0x0001	COM11 - Generic Pro..				14	32767
0x0003	COM11 - Generic Pro..				8	32767
26 (0x1A) - 2480 MHz		0x0022		Unknown (0x00)		
0x0000	COM11 - Generic Pro..				8	32767
0x0001	COM11 - Generic Pro..				8	32767
0x0003	COM11 - Generic Pro..				8	32767

Fig. 12. Channels scan



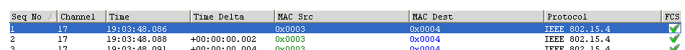
Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	23	19:13:19.769		0x0000	Broadcast (0xffff)	IEEE 802.15.4	✓
2	23	19:13:20.018	+00:00:00.249	0x0000	Broadcast (0xffff)	IEEE 802.15.4	✓
3	23	19:13:20.024	+00:00:00.006	0x0001	0x0000	IEEE 802.15.4	✓
4	23	19:13:20.054	+00:00:00.030	0x0003	0x0000	IEEE 802.15.4	✓
5	23	19:13:20.266	+00:00:00.212	0x0000	Broadcast (0xffff)	IEEE 802.15.4	✓

(a) Scan of Control channel $N°$ 23



Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	11	19:01:59.916		0x0001	0x0002	IEEE 802.15.4	✓
2	11	19:01:59.918	+00:00:00.002	0x0001	0x0002	IEEE 802.15.4	✓
3	11	19:01:59.921	+00:00:00.004	0x0001	0x0002	IEEE 802.15.4	✓

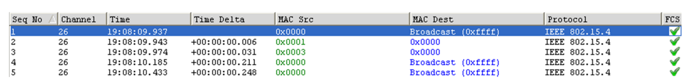
(b) Scan of Data channel $N°$ 11



Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	17	19:03:48.086		0x0003	0x0004	IEEE 802.15.4	✓
2	17	19:03:48.088	+00:00:00.002	0x0003	0x0004	IEEE 802.15.4	✓
3	17	19:03:48.091	+00:00:00.004	0x0003	0x0004	IEEE 802.15.4	✓

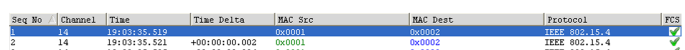
(c) Scan of Data channel $N°$ 17

Fig. 13. Scan of channels $N°$ 23 , 11 and 17



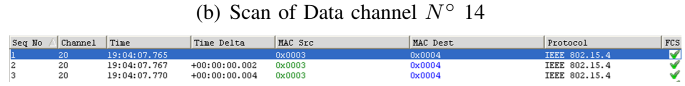
Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	26	19:08:09.937		0x0000	Broadcast (0xffff)	IEEE 802.15.4	✓
2	26	19:08:09.943	+00:00:00.006	0x0001	0x0000	IEEE 802.15.4	✓
3	26	19:08:09.974	+00:00:00.031	0x0003	0x0000	IEEE 802.15.4	✓
4	26	19:08:10.185	+00:00:00.211	0x0000	Broadcast (0xffff)	IEEE 802.15.4	✓
5	26	19:08:10.433	+00:00:00.248	0x0000	Broadcast (0xffff)	IEEE 802.15.4	✓

(a) Scan of Control channel $N°$ 26



Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	14	19:03:35.519		0x0001	0x0002	IEEE 802.15.4	✓
2	14	19:03:35.521	+00:00:00.002	0x0001	0x0002	IEEE 802.15.4	✓
3	14	19:03:35.525	+00:00:00.004	0x0001	0x0002	IEEE 802.15.4	✓

(b) Scan of Data channel $N°$ 14

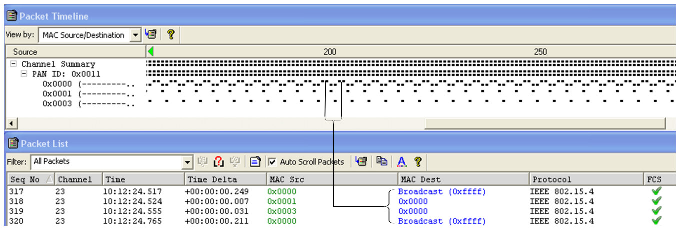


Seq No	Channel	Time	Time Delta	MAC Src	MAC Dest	Protocol	FCS
1	20	19:04:07.765		0x0003	0x0004	IEEE 802.15.4	✓
2	20	19:04:07.767	+00:00:00.002	0x0003	0x0004	IEEE 802.15.4	✓
3	20	19:04:07.770	+00:00:00.004	0x0003	0x0004	IEEE 802.15.4	✓

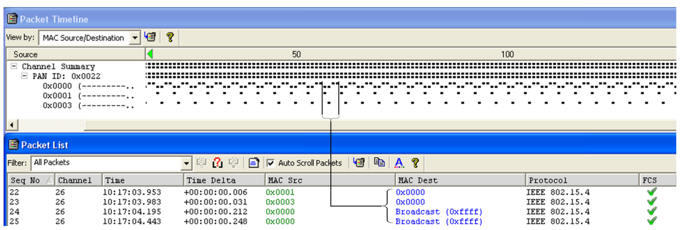
(c) Scan of Data channel $N°$ 20

Fig. 14. Scan of channels $N°$ 26 , 14 and 20

- Packet timeline: As done previously, we have analyzed the scan of the control channels of each PAN (i.e., channel N°23 for PAN1 and channel N°26 for PAN2) over time to verify the operation of the control part of the PMCMTP. According to Figure 15, we note that using the channel N°23 (resp. the channel N°26): periodically, the coordinator of PAN1 (resp. PAN2) sends the first beacon to synchronize its network, then source nodes according to their id, if they want, they send a resource request to their coordinator to reserve resource. At the end of the resource transmission phase, the coordinator of each PAN sends the second beacon including the necessary information of served resource requests.



(a) Scan of Control channel $N°$ 23



(b) Scan of Data channel $N°$ 26

Fig. 15. Scan of channels $N°$ 23 and 26

Compared to Figure 4, illustrating the principle of the PMCMTP operation, these results confirm the correct operation of the PMCMTP inside both PAN1 and PAN2.

B. Simulation PMCMTP Evaluation

In this subsection, we evaluate the performance of the PMCMTP by simulation. We assume that UWB network is used running at 850Kbps. In all experiments, we simulate a synchronized network of 9 PANs, each occupies hexagonal cell of radius $R = 5m$. Each PAN has 25 nodes uniformly distributed (One PAN coordinator, twenty routers and four BSNs coordinators). For each active PAN, we assume that nine nodes initiate gossip CBR streams towards the sink nodes and each source node generates a packet in every time slot. Each PAN coordinator is characterized by its superframe duration $\{PAN_i = (SD_i, BI_i)\}_{1 \leq i \leq 9}$. Table I shows the default value of each parameter in the simulations. We assume that there are several sink nodes in each PAN.

TABLE I
SIMULATION PARAMETER

Parameter	Default value
Number of PANs, Nodes per PAN	$9, 25$
Communication rate	$850 Kbps$
System Load	*9 packets per PAN per Time slot*
Traffic pattern	*Gossip CBR Streams*
Radio range	*5m for control, 2m for data*
Max MSDU length	*104 Bytes*
Time slot duration for data transfer	$0.984ms$
Time slot duration for resource request	$0.246ms$
SO_{min} *for data communications*	4
Network Duty Cycle	*See Figure 2*

We use the global throughput as a metric to analyze and compare the behavior of the PMCMTP, MCMAC and TDMA (Time Division Multiple Access) protocols. Figure 16 shows that, both the MCMAC and TDMA protocols present almost a static behavior. We note that both PMCMTP and MCMAC, MAC multi-channel access protocols, out perform TDMA protocol given that they allow several simultaneous communications. Compared to MCMAC, the PMCMTP protocol exhibits better performance given that MCMAC allows only one PAN to be active and it allocates data channels for a fixed duration which may introduce additional communication overhead. The PMCMTP protocol makes its proof to guarantee the enhancement of the throughput of the global network. This guarantee comes from the exploitation of the dynamic data channel allocation policy based on PANs duty cycles information and spacial frequency reuse that avoid the under-utilization of spectrum resource and maximizes the number of used channels per active PAN.

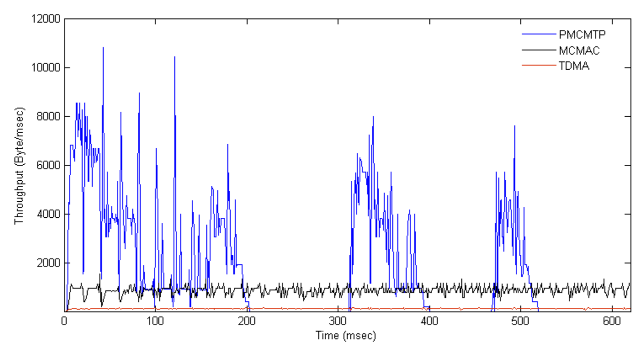


Fig. 16. Throughput vs Time

VII. CONCLUSION

In this paper, we have presented the implementation details of the PMCMTP multi-channel multi-time slots MAC protocol in nesC/TinyOS environment for the Crossbow MICAz motes. Two scenarios with respectively one PAN of five motes and two PANs with five motes each one, were used to test, validate and demonstrate the effective operation of the proposed MAC protocol. This set of experiments shows the feasibility of the Multi-channel multi-time slots access mechanism, proving that it can be used in real environments. The PMCMTP's performance has been evaluated by simulation showing that our protocol exhibits prominent ability to ensure QoS enhancement compared to MCMAC and TDMA protocols. However, the evaluation of the performance of the PMCMTP, via a realistic testbed setting, remains very encouraged that we will tackle in next work.

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