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Advantages of Dual Channel MAC for Wireless Sensor Networks

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***Abstract*— Traditional low cost radios for wireless sensor networks operate with one frequency channel at any given time. However, recent advances in radio hardware for WSNs made available transceivers that can support two simultaneous channels. In this work, we investigate the benefits of using two parallel independent frequency channels at the MAC layer. In particular, the paper introduces a technique of Dual Channel Multiple Access with Adaptive Preamble (DCMA/AP). The protocol uses two separate frequencies for data and control packets to avoid the use of handshake mechanisms (e.g. RTS/CTS) in order to reduce energy consumption and packet delay. To address the hidden and exposed terminal problems, DCMA/AP enables a receiver to send a busy tone signal on the control channel to notify neighbors that an ongoing reception is in progress. As a result, packet collisions are nullified with an increase of node throughput. Furthermore, an adaptive preamble mechanism in DCMA/AP avoids secondary processes of node synchronization together with a reduction of idle listening of receiving nodes that are considered to be one of the major sources of energy consumption in wireless sensor networks. Finally, DCMA/AP introduces a mechanism of opportunistic crossover speeds up the process of packet forwarding by pre-announcing the successive candidate node intended to receive the packet.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) typically consist of a large number of tiny and inexpensive devices (nodes) which sample data from the environment together with few more powerful nodes (gateways) to collect the sampled information. Normally, nodes and gateways operate cooperatively to achieve a task. Sensor networks have a wide application space that ranges from civilian to military application and have a common set of requirements. In general, WSNs are employed in long unattended operations sometimes in harsh environments that require self-organization, energy efficiency and adaptivity. In fact, nodes should collaborate locally in different parts of the network to enforce energy efficient self-management policies without impacting data delivery. Such a process must be done within an adaptive context since some nodes' battery resources might be depleted over time, while others can join the network later. Usually, changing the battery of depleted nodes is not practical, because the deployment area in many applications may not be easily accessible. The use of low cost devices for wireless sensor networks has brought researchers to develop multiple access procedures primarily oriented towards the usage of a single channel transceiver [1], [2]. Although such a direction of research is still dominant, recent advances in radio hardware manufacturing have enabled the development of a low-cost and low-energy transceiver that can effectively receive on two parallel frequencies with a relative small increase of energy consumption. An example is the nRF2401 transceiver [3] effectively employed on motes in [4], developed at the University of Cork, Ireland. Table II shows the specification of that transceiver. The current MAC protocol employed uses one frequency only. This paper describes a technique of Dual Channel Multiple Access with Adaptive Preamble (DCMA/AP). The protocol exploits two parallel frequency channels to efficiently manage the limited resources in terms of node energy consumption and packet delay. We emphasize that the DCMA/AP protocol can be used for any transceiver that supports two frequency channels, in this way while the first channel is transmitting, the second one is listening.

The remainder of the paper is organized as follows. Section II discusses the motivation for this novel MAC protocol. Section III presents the related work. Section IV discusses the DCMA/AP protocol in detail. Section VI concludes the paper with a description of ongoing implementation and future work.

II. MOTIVATION

Although the scientific literature shows a profusion of energy efficient protocols, use of dual frequencies for wireless sensor networks has not yet been explored. This is primarily due to the desire to keep hardware platforms relatively simple and consequently inexpensive. Furthermore, two radios within the same devices typically consume double the amount of energy, which does not suit most WSNs. However, recent advances in semiconductor research have allowed to cut the cost and the energy consumption of transceivers with simultaneous reception of two parallel independent frequency channels for sensor nodes.

The driving motivation of this work is to investigate the benefits of two independent channels at MAC layer that support transmission on the first channel and simultaneous reception on the second one. The protocol can is tailored for applications that require:

- Low packet transmission latency: The use of handshake mechanisms like RTS/CTS/ACK together with a rather low node duty cycle cause significant packet delay. Studies in [5], [6], [7] have demonstrated that such latency can be up to tens of seconds for packets which are located few hops from the gateway and is notably amplified as the activity of nodes decreases. Such a delay renders handshake protocols unsuitable for mobile nodes or applications where a prompt response is a needed, such as detection of moving objects, harmful gas detection, or critical medical applications.
- Energy efficiency: Energy savings can be achieved by reducing idle listening [2], which is due to nodes that periodically listen to the channel even if no message has been sent or that listen to messages not intended to them. Furthermore, the avoidance of handshake mechanisms can reduce the energy consumption caused by control packet overhead and switching overhead that have been demonstrated to be a significant source of energy wastage in [8], [7].
- Reduced control overhead: Avoiding handshake mechanisms can effectively improve the channel utilization by removing the exposed terminal problem depicted in figure 1.
- Minimal synchronization: Avoiding any periodic broadcast of synchronization packets among neighboring nodes reduces the complexity of network management.
- Minimal scheduling: Our protocol improves scalability by avoiding complex node allocations that are typical of scheduling protocols or TDMA-based protocols.
- Maximal adaptivity and autonomy: We expect our protocol to yield an overall improvement in the adaptivity, self-management and autonomy of the network through independent and dynamic locally adaptive node duty cycles.

III. RELATED WORK

Many MAC protocols have been proposed for wireless networks [9]. The works in [10] and [11] have proposed the use of out-of-band signalling to indicate that the data channel is busy. Busy Tone Multiple Access (BTMA) [10] suggests having a separate busy tone channel to solve the hidden terminal problem of classic Carrier Sense Multiple Access (CSMA). BTMA proposes that when a centralized base station senses a busy data channel, it places a sine wave on the busy tone channel to prevent any nodes from transmitting. Dual Busy Tone Multiple Access (DBTMA) [11] has presented a recent extension of using busy tones, where two out-of-band busy tone channels are used to protect RTS transmissions, and to prevent nodes in the receiver's vicinity from transmitting. By offering a distributed approach instead of a base station, DBTMA presents a viable method of a busy tone solution to the hidden terminal problem in ad hoc networks. In this work, we apply the concept of out-of-band busy tones to sensor networks and we present a MAC mechanism that eliminates the need for handshaking.

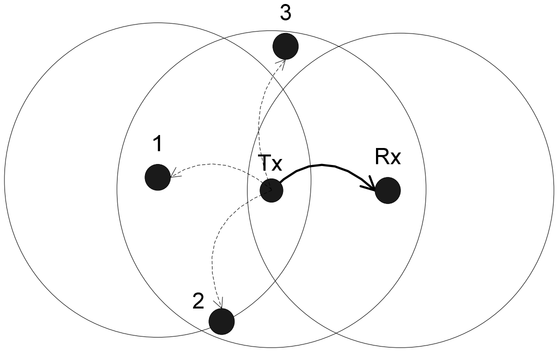

Fig. 1. The external terminal problem (ETP) of the RTS/CTS/ACK handshake mechanism does not allow simultaneous communication of nodes around the transmitter (e.g. 1,2,3). Therefore, ETP causes an inefficient use of the channel.

TABLE I

nRF2401 SPEC

Parameter	**Value**	**Unit**
Minimum Supply voltage	1.9	V
Data rate (up to 1Mbps)	250	Kbps
Operating frequency	2.4 - 2.5	GHz
Average supply current in power down	400	nA
Average supply current in stand-by mode	12	μA
`Transmitter operation`		
Supply current one channel in transmit	10.5	mA
Output Power in transmit	-5	dBm
`Receiver operation`		
Supply current one channel in receive	18	mA
Supply current two channels in receive	23	mA
Sensitivity at 0.1% BER (at 250 Kbps)	-90	dBm
`Timing`		
Power Down → Active mode (RX/TX)	3	μs
Stand-By → Active mode (RX/TX)	202	ms
TX → RX or RX → TX	5	μs
Time on air, TX Direct mode	4	ms

TABLE II

nRF2401 TRANSCEIVER DATA SHEET

Within sensor networks, idle listening constitutes a large portion of power consumption since data is sent infrequently. This effect is even more pronounced in monitoring sensor networks. Thus, energy-efficient MAC protocol proposals have focused on minimizing idle listening at sensor nodes [1], [2], [12].

IEEE 802.15.4 [12] is a standard with physical and MAC layer specifications for low rate, low power, short range networks, including sensor networks. IEEE 802.15.4 specifies a plethora of functionality choices, many of which may never be used. As a result, several researchers have proposed new MAC protocols on top of the 802.15.4 PHY layer.

SMAC [2] constitutes a heavyweight MAC protocol for sensor networks that relies on time synchronization and scheduling among nodes to enforce periodic sleep and listen schedules. SMAC reduces energy consumption and provides scalability at the cost of per-hop fairness, throughput, and latency.

The recent work by Polastre et al. proposes BMAC [1], as a lightweight sensor network MAC protocol that aims at providing versatile medium access while keeping the MAC functionality as simple as possible. Because it is an asynchronous protocol, BMAC eliminates the communication and processing overhead for scheduling and synchronization, which reduces energy consumption. BMAC enables each node to wake up periodically to check for channel activity. The wake-up period is referred to as the check interval. BMAC defines 8 check intervals, and each check interval corresponds to one of BMAC's 8 listening modes. To ensure that all packets are heard by the nodes, packets are sent with a preamble whose reception time is longer than the check interval. BMAC therefore defines 8 different preamble lengths referred to as transmit modes. Additionally, Polastre et al. analytically derive optimal listening modes based on the number of neighbors of a node. In their experiments, they determine the maximum neighborhood size in the network, and they set the optimal listening mode for that neighborhood size. The experimental results yield significant energy savings for BMAC over previous protocols, such as SMAC. Our work adopts a similar matching of preambles and check intervals in BMAC and couples it with out-of-band busy tones to further reduce power consumption in sensor networks.

IV. The DCMA/AP Protocol

The dual frequency channel multiple access with adaptive preamble (DCMA/AP) is based on simultaneous utilization of two frequency channels called Data channel (**Cd**) and Control channel (**Cc**). The next subsection describes the use of Cd and Cc in detail together with the content of different types of control packets. The successive subsection addresses the main mechanisms of access to the channel of DFMA. The final subsection ends with two important techniques of latency and energy consumption reduction, namely the adaptive preamble and the opportunistic packet crossover.

A. Functions of Data and Control channels

In DCMA/AP, the two available channels are distinctively utilized for control packets and data packets. Table III describes the details of control packets transmitted on Cc. DCMA/AP use control packets to notify neighboring nodes that the channel Cd is busy for the entire duration of the transmission. Only the receiving node is allowed to transmit on Cc for activity notification. In fact, the receiver is the only node that can effectively inform the neighborhood that a reception is in progress on channel Cd. Therefore, only nodes around the receiver will refrain from transmitting, as shown in figure 2, which effectively eliminates the exposed terminal problem.

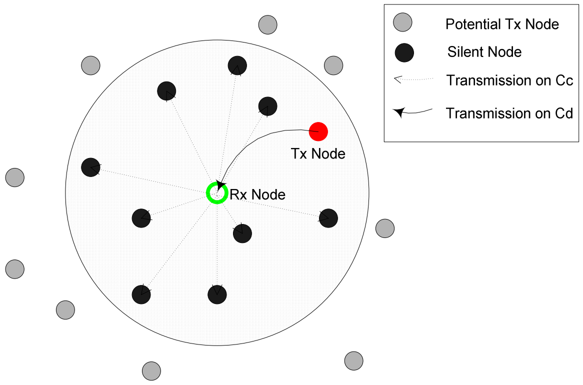

Fig. 2. During a transmission, the receiver notifies the neighborhood of a reception in progress, RIP packet. Nodes not within the receiving node range can still access the channel as a result.

Packet	Content
Adaptive preamble **Pl**	RxID, Data length. TxID
Reception in progress **RIP**	RxID, TxID, transm. length, next RxID
Error3 Report **ERR**	short burst tone

TABLE III

Packet types used to notify the transmission states. TxID = ID of transmitting node, RxID = ID of the receiving node (NUL for local broadcast packet)

B. Mechanism

In DCMA/AP, nodes assess the channel Cc by means of short *listening periods* **Tc** followed by long *sleeping intervals*, **Ts**. The protocol does not need any synchronization procedure between nodes. Therefore, nodes wake up and go into sleep at different time, which is referred to as *asynchronous transmission*. A node Tx that has data to send senses Cc for a short random period in a contention window referred as Tc, or the time for *clear channel assessment* (**CCA**).

Figure 3 depicts the MAC layer interactions. If Cc is free it means no neighboring nodes are currently in reception phase. Hence, the Tx node can start the wake up process for the intended receiver Rx by transmitting a long preamble Pa on the channel Cd and listening simultaneously to the channel Cc. The preamble has a maximum length of **Tp**. Setting Tp greater than Ts guarantees that the receiver will hear part of the preamble. When the Rx node hears the ongoing Pa, it sends a **RIP** packet on the channel Cc. The RIP packet, which contains the transmission length, has two important functions: (1) it acts as a notification for the receiver's neighboring nodes that a reception is in progress; and (2) it enables adaptivity of the preamble length as described in section IV-D. Each neighbor of the receiver will then enters the sleep mode after setting up a count-down timer, similar to the network allocation vector in the IEEE 802.11 [13]. A neighbor will wake up after the timer reaches zero. A node that has data to send can determine whether the channel is busy by first looking at the timer.

If the node Tx finds the channel Cc busy, then it gets the transmitted info, sets the NAV accordingly and goes into

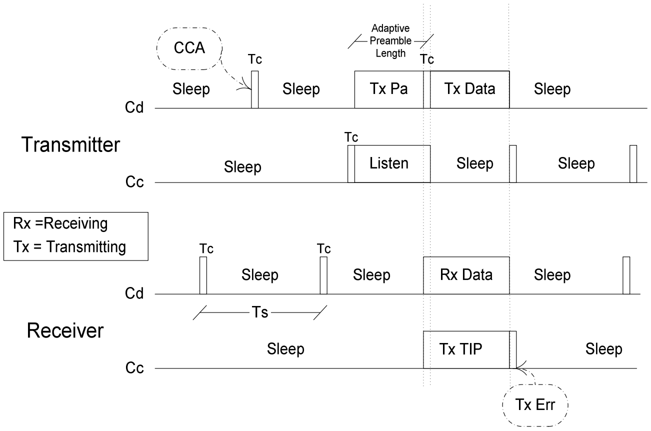

Fig. 3. Transmission mechanism of DCMA/AP: first the transmitter senses Cc then it starts transmitting a long preamble on Cd. The data packet is sent when the receiver notifies the sender of its presence.

sleep. Tx will wake up after the NAV reaches zero and repeat the process. Finally, DCMA/AP provides an *Err period* to notify errors in transmission. The Err period is located on the channel Cc at the end of the packet transmission. It consists of a short burst tone. In case of transmission error, the packet will be rescheduled after an exponential random back-off procedure. In order to obtain the notification of a failure after communicating , the transmitter has to listen to the channel Cc as shown in figure 3.

C. The synchronization issues

Two relevant problem related to the energy utilization and packet overhead within sensor networks are the idle listening at the receiver and the process of periodic node synchronization. In fact, Idle listening at the receiver is one of the major causes of energy wastage especially in conditions of low traffic in the network [2].

As mentioned earlier, the sensor hardware is of low cost hence timing characteristics of sensor devices are not very accurate. As a consequence, the internal timers are likely to be affected by random deviations due to external phenomenon like temperature, humidity, pressure etc. that increase the clock skew over time. Such variations differ from one sensor to another. Furthermore, nodes alternate their periods of activity with periods of sleeping by a certain duty cycle. Enabling nodes in a neighborhood to wake up simultaneously and communicate requires that timer skews are compensated for periodically. In particular, synchronization protocols should be able to compensate for both the node offset time to synchronize wake-up times and the frequency skew of each sensor internal clock. While the former is usually achieved by local broadcasts of synchronization packets, the latter involves flooding sync packets from the base stations, which are supposed to be perfectly synchronized. The whole process causes large packet overhead hence a commensurate increase of energy consumption.

In order to avoid the aforementioned issues, DCMA/AP is inspired by the solution used by Aloha in [4] and the low power listening mechanism (LPL) in MAC [1]. Such protocols use a long wake up preamble transmitted before the data packet. The maximum preamble length is optimally derived through analytical calculations based on the number of neighbours of nodes. Such solution allows shifting the synchronization and idle listening problems of nodes from the receiver to the transmitter which is a rarer case due to the general low traffic of the network.

D. Adaptive Preambles in DCMA/AP

DCMA/AP enhances the solution in [1] by dynamically adjusting the preamble length through use of the alternative control frequency as follows: All nodes in the network have a very low duty cycle (which can be less than 1%). Nodes wake up periodically to check for node activity within its range, this period between two consecutive checking is referred as *inter-check interval* of length Ts (*sleeping time*). The length of such an interval is optimally derived based on the neighborhood size as in [1]. If nothing is heard, the node goes to sleep immediately and wakes up again after one Ts. A node that has a packet to transmit uses a *long preamble* **Pa** to wake up the intended receiver. The maximum length of Pa is set to Tp. To ensure the intended receiver can wake up and listen to the preamble, it is necessary that $Tp > Ts$. When the receiver nodes listen to `Pa` then it uses the control channel Cc to enable the communication back to the transmitter. At this point, the transmitter can start sending its data packet immediately. Because the receiver is aware of the imminent transmission, it stays awake so that the sender can transmit the data packets without any long preambles. This mechanism permits to adapt the long preamble with respect to the receiver response. The preamble `Pa` contains the *transmitter* `ID` and the *receiver* `ID`. Such couple of IDs is repeated for the whole duration of the preamble. A *dividing code* is transmitted between two adjacent couples. In the case of local broadcast packets, no receiver is identified. This implies that the transmission of the data packet start right after the time Tp. In fact, the time Tp ensures all neighboring nodes are in receiving mode. The AP mechanism allows a decrease of: (1) packet overhead due to synchronization packets and (2) idle listening at the receiver.

1) Simultaneous preambles: The asynchronous access to the channel of DCMA/AP can result in simultaneous preamle transmission on Cc. In such a case, the channel can be allocated if at least one couple of IDs is correctly received. Figure 4 shows the case when the node receiver wakes up during a multiple transmission of the preamble. In such a case, the receiver will still be able to listen to the preamble that finish later. The reception will fail only in case two nodes wake up simultaneously. This is a rare case because of the asynchronous wake up time of nodes. Therefore, DCMA/AP does not need any periodic local broadcast of sync packets, which yields energy savings. We need to clarify that the transmission of the long preamble can causes collisions on the data channel Cd. However, nodes wake up, sense the channel and start transmitting the preamble Pa at different time. As above described, Pa consists of a set of ID couple continuously

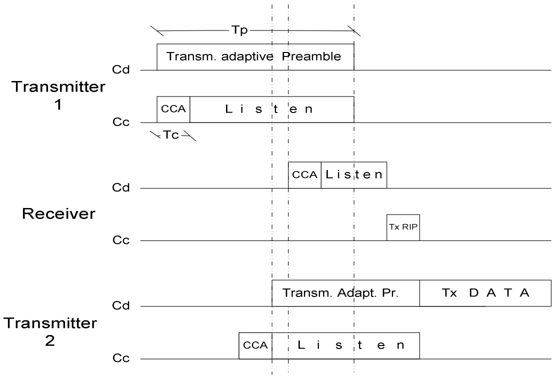

Fig. 4. Concurrent transmission of two preambles on the channel Cc to the same receiving node;

transmitted. Therefore, in case of a receiving node wakes up during several preamble transmissions, it will still be able to receive the couple ID of the last node that have started the transmission. This will only be the case as long as the last couplet transmission of the preamble occurs after the first node has ceased transmission of its preamble. The receiver will enable the transmission through the Cc channel as soon as the first ID couple is correctly received. At this point any further contention will cease by putting all other neighbouring nodes of the receiver into sleep. The probability that the destination node does not receive correctly any ID couple is comparable to a collision of RTS.

E. The Opportunistic Crossover

In the above discussion, we have illustrated that during an ongoing communication, the receiver uses the control channel Cc to notify neighboring nodes of a *Reception In Progress* (**RIP**). As described in section IV-B, the RIP packet contains the duration of the data packet being sent and ID of the next intended receiver node, *next ID*. We also mentioned that nodes wake up periodically to check for activity in channel Cd and in case of activity detection they would also check the channel Cc. Therefore, the next ID node can opportunistically listen to the transmitted RIP from the current receiving node. As a result, the next ID node will be able to synchronize its NAV in a way that it will wake up right at the beginning of the successive preamble. The next receiver is then in a position to enable immediately the forwarding activity by means of its RIP packet. By providing an implicit synchronization between the receiving node and the next intended one, this *opportunistic crossover* permits a drastic reduction of the long preamble so that both latency of packet forwarding and energy consumption are reduced.

F. Timing analysis

As previous mentioned, the DCMA/AP protocol allows shifting the problem of idle listening from the receiver to the transmitter as BMAC does. For this reason, this section investigates the time needed for a successful transmission of a packet between two neighbouring nodes within DCMA/AP. Consequently, a timing comparison against BMAC is given.

The total times needed for a packet transmission are referred to as T_{Slot}^{DCMA} and T_{Slot}^{BMAC} for DCMA and BMAC respectively.

The DCMA/AP protocol results in:

$$T_{Slot}^{DCMA} = T_C + T_{sRT} + T_{Pa} + T_{sTR} + \tag{1}$$

$$+ \quad T_{IDs} + T_{sRT} + T_d + T_{sTR} + T_{cca}$$

where $T_C = T_{turnOnRadio} + T_{cca}$; T_{sRT}, T_{sTR} are the switching times between transmit and receive and vice versa; we assume $T_{sRT} = T_{sTR}$; T_{IDs} is the time to listen to one ID couple;

The transmission mechanism of BMAC consists of a long preamble followed by RTS/CTS/Data/ACK. The long preamble is not adaptive. As a result:

$$T_{Slot}^{BMAC} = T_C + T_{sRT} + T_{lp} + T_{rts} + \tag{2}$$

$$+ \quad T_{sTR} + T_{cts} + T_{sRT} + T_d + T_{sTR} + T_{ack}$$

Since the time needed for RTS or CTS or ACK is almost equivalent to the time needed to obtain an ID couple in DCMA, it can be assumed:

$$T_{rts} = T_{cts} = T_{ack} = T_{IDs} = T_{sense}$$

Furthermore, the time of BMAC's long preamble T_{lp} has to be greater than the node sleeping time T_S, hence

$$T_{Slot}^{BMAC} - T_S - 2T_{sense} > T_{Slot}^{DCMA} - T_{Pa} + T_{cca}$$

This implies:

If $T_S = T_{Pa}$ (that is when the receiving node wakes up at the end of the adaptive preamble: worst case)

$$T_{Slot}^{BMAC} - T_{Slot}^{DCMA} > 2T_{sense} - T_{cca} \tag{3}$$

If $T_S/2 = T_{Pa}$ (that is when the receiving node wakes up at in the middle of the adaptive preamble: average case)

$$T_{Slot}^{BMAC} - T_{Slot}^{DCMA} > T_S/2 + 2T_{sense} - T_{cca} \tag{4}$$

If $T_{Pa} = 0$ (that is when the receiving node wakes up ad the beginning of the adaptive preamble: best case)

$$T_{Slot}^{BMAC} - T_{Slot}^{DCMA} > T_S + 2T_{sense} - T_{cca} \tag{5}$$

All cases show a large decrease of local packet transmission latency for DCMA/AP with respect to BMAC. It is interesting to notice that by using the opportunistic crossover mechanism, we increase the probability of obtaining the best case as next forwarding nodes will tend to synchronize their wake up time right at the beginning of the successive preamble.

V. RESULTS AND FUTURE WORK

DCMA/AP has been coded within the OmNet++ modular simulation environment based on the object oriented C++ computer language. For a more complete evaluation, the simulator has been modified to support node mobility.

Preliminary results show a decrease of transmission packet delay together with an increase of network flexibility in terms of access to the channel and node scalability. Such results are primarily due to the absence of any fixed scheduling for nodes in the network. In fact, the system is completely asynchronous so that new nodes can join the network without any synchronization procedure. Furthermore, the nonexistence of RTS/CTS handshake mechanism allows an improved channel utilization together with a good response of the protocol when mobile nodes are deployed. The former is due to the removal of the exposed terminal problem by enabling the receiving node to locally broadcast a RIP packet for the entire duration of the transmission.

Some other initial results show an increase of partial overlapping transmissions on the control channel. In such cases the receiving node listens to a longer portion of the adaptive preamble to get the ID couple that will enable the data transmission. This implies an increase of receiving node activity hence energy consumption. The opportunistic crossover described in section IV-E shows notable improvements in terms of message passing delay between neighbouring nodes. In fact, the crossover is almost comparable to an implicit node synchronization between the receiving node and the next one scheduled. Finally, some transmission errors due to bad channel conditions or too low power at the receiver can be notified by means of the *Err transmission period*. Such circumstances cause a reschedule of the packet after a random exponential back-off procedure.

Although DCMA/AP seems to follow our general expectations, these results are yet preliminary. Later works will include elaborate results in terms of relevant metrics for wireless sensor networks such as energy consumption, latency of messages, control packets overhead, scalability and aptness to node mobility. In particular imminent works will:

- Compare the protocol with WSNs MAC that uses one frequency channel (e.g SMAC [7] and BMAC [1]);
- Compare the protocol with MAC for ad-hoc networks that use two frequency channels (e.g BTMA [11] , DBTMA [10]);
- Implement DCMA/AP on a real mote that supports two simultaneous frequencies for transmission of one channel and reception of the other one;
- implement DCMA/AP on the real hardware in accordance with previous synthetic results.
- Include DCMA/AP with MERLIN [14] as a routing layer for wireless sensor networks;

VI. CONCLUSION

In this paper we have presented a preliminary version of dual frequency channels multiple access with adaptive preamble for wireless sensor networks. The motivation for this protocol has been to exploit the usage of two simultaneous channels in low-cost and low power consuming transceivers. The primarily requirement is that the radio transceiver supports transmission on the first channel and simultaneous reception on the second one. The paper investigated the advantages of using the two channels distinctively for control packets and data packets. The mechanism avoids any handshake mechanism between nodes to reduce long packet delays of other protocols for wireless sensor networks. Unlike in RTS/CTS based protocols, in DCMA/AP the receiver notifies an ongoing reception in progress through the alternative channel. As a consequence, the protocol can improve the channel utilization by removing the exposed terminal problems. The two channels permitted also to effectively use a long adaptive preamble that reduce the idle listening at the receiver so producing relevant energy saving. As a result, no synchronization processes between nodes are necessary. Finally DCMA/AP exploits the opportunistic crossover mechanism to accelerate the process of packet forwarding between neighboring nodes.

REFERENCES

[1] J. Polastre, J. Hill, and D. Culler, “Versatile low power media access for wireless sensor networks,” in *ACM SenSys*, 2004.

[2] W. Ye, J. Heidemann, and D. Estrin, “An energy-efficient mac protocol for wireless sensor networks,” in *Proceedings of the IEEE Infocom*, USC Information Sciences Institute. New York, NY, USA: IEEE, June 2002, pp. 1567–1576.

[3] N. semiconductor, “nrf2401 datasheet,” Nordic, Tech. Rep., 2002.

[4] *The Development of a Novel Miniaturised Modular Platform for Wireless Sensor Networks*, UCLA. Los Angeles, California: IEEE, Apr 2005.

[5] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, “Energy-efficient collision-free medium access control for wireless sensor networks,” in *SenSys03: Proceedings of the 1st international conference on Embedded networked sensor systems*. New York, NY, USA: ACM Press, 2003, pp. 181–192.

[6] B. Krishnamachari, G. Lu, and C. Raghavendra, “An adaptive energy-efficient and low-latency mac for data gathering in sensor networks,” in *Wireless, Mobile, Ad Hoc and Sensor Networks (WMAN 04)*, Apr. 2004.

[7] W. Ye, J. Heidemann, and D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks,” *IEEE/ACM Trans. Netw.*, vol. 12, no. 3, pp. 493–506, 2004.

[8] A. G. Ruzzelli, P. Cotan, R. Tynan, and G. O’Hare, “Energy consumption of mac protocols under different hardware platforms for wireless sensor networks,” *Elsevier Journal special issue in Mac protocols for Wireless sensor networks*, Jan 2006.

[9] R. Jurdak, C. V. Lopes, and P. Baldi, “A survey, classification, and comparative analysis of medium access control protocols for ad hoc networks,” *IEEE Communications Surveys and Tutorials*, vol. 1, pp. 2–16, 2004.

[10] F. A. Tobagi and L. Kleinrock, “Packet switching in radio channels: Part ii-the hidden terminal problem in carrier sense multiple-access and the busy-tone solution,” *IEEE Transactions on Communications*, vol. 23, no. 12, pp. 1417–1433, December 1975.

[11] Z. J. Haas and J. Deng, “Dual busy tone multiple access (dbtma)- a multiple access control scheme for ad hoc networks,” *IEEE Transactions on Communications*, vol. 50, no. 6, pp. 975–985, June 2002.

[12] IEEE802.15.4., “Wireless medium access control (mac) and physical layer (phy) specifications for low-rate wireless personal area networks (lr-wpans).”

[13] IEEE, “Wireless lan medium access control and physical layer specification,” *ANSI/IEEE Standard 802.11*, 1999.

[14] A. Ruzzelli, L. Evers, S. Dulman, L. V. Hoesel, and P. Havinga, “On the design of an energy-efficient low-latency integrated protocol for distributed mobile sensor networks,” *IWWAN International Workshop on Wireless Ad hoc Networks*, June 2004.