OMA: a Multi-channel MAC Protocol with Opportunistic Media Access in Wireless Sensor Networks

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Abstract—**To tackle control channel saturation problems, this paper proposes OMA, an asynchronous duty cycle based multi-channel MAC protocol with opportunistic media access for wireless sensor networks. By adopting opportunistic media access, OMA effectively alleviates, if not completely eliminates, control channel saturation problems. More importantly, OMA is fully distributed with no requirements of time synchronization or multi-radio. Therefore, OMA is very easy to be implemented in resource-constrained sensor nodes. Via the theoretical analysis, the opportunistic probability with which a node opportunistically access the control channel is obtained. To validate the effectiveness of opportunistic media access, extensive simulations and real testbed experiments were conducted. The simulation and experimental results show that when the number of channels is large or the network loads are heavy, OMA improves energy efficiency and throughput significantly compared with other works in the literature.**

I. INTRODUCTION

Emerging as one of the dominant technology trends, wireless sensor networks (WSNs) have a wide range of potential applications [1]. To support these applications, a larger number of MAC protocols have been proposed. Unfortunately, even though multiple channel are available in existing sensor hardware such as MICAz and Telos, mainstream MAC protocols in the WSNs literature still focus on single channel solutions [2]. Recently, to overcome the drawbacks of single channel MAC protocols, some multi-channel MAC protocols (**mcMAC**) have been proposed to improve network performance via parallel communication, *e.g.*, MMSN[2], Y-MAC[3], PMC[4], Hy-MAC[5], and TFMAC[6]. The mcMACs have several advantages as follows. *First*, since generally mcMACs employ one Control Channel (**CC**) to send control information and multiple Data Channels (**DC**) to send data, the overall channel utilization is increased. *Second*, since communications on different orthogonal channels do not interfere with each other, mcMACs have higher throughput and shorter latency. *Third*, because current off-the-shelf WSNs radios already offer multiple channels [2] (*e.g.*, the IEEE 802.11 a standard provides 12 channels, and MICA2 motes support more than 50 channels), mcMACs incur no more hardware cast, *i.e.*, multi-radio.

A mcMAC mainly consists of *channel selection* and *media access*. Channel selection decides how to select idle channels for all the nodes efficiently in order to optimize the performance of WSNs; whereas, media access decides when and how all the nodes access the channels that have been selected for them to avoid the data packet collisions. Channel selection schemes can be classified as *static* and *dynamic* ones based on the frequency of channel selection execution. Media access schemes fall in two categories: *TDMA* and *CSMA* according to whether all the nodes in the WSNs are synchronized.

Dynamic channel selection and CSMA with duty cycling are jointly considered as suitable schemes for WSNs because of three reasons as follows. *First*, dynamic channel selection schemes require less number of channels than static schemes [7]. *Second*, CSMA involves no overhead of time synchronization required by TDMA. *Third*, duty cycling is a scheme to address the idle listening problem in WSNs, which is considered as one of the largest sources of energy consumption in WSNs [2]. However, these combined schemes sometimes fail to offer satisfactory performance due to the *Control Channel Saturation problems* (**CCS**), which undermines the network performance of WSNs. We will verify CCS in Section III.

In this paper, aiming at CCS, an asynchronous duty cycle based multi-channel MAC protocol with opportunistic media access is proposed called OMA. Involving no overhead of time synchronization and multi-radio, OMA is tailored to overcome CCS. The key novelty of this work is to use the opportunistic media access to transmit control packets on the control channel to alleviate the control channel saturation problem. Therefore, OMA is capable of alleviating the collisions of control packets on the control channel, and improving network throughput and energy efficiency. The contributions of this work are as follows.

- To the best of authors' knowledge, this paper makes the first attempt to define and to verify the control channel saturation problems under WSNs context.
- This paper proposes a duty cycle based multi-channel MAC protocol, which applies an opportunistic media access scheme to effectively handle the control channel saturation problem.
- This paper analyzes the performance of OMA, and obtains the opportunistic probability via correlating it with the real time network parameters. No previous work gives such an analysis.
- The extensive simulation results show that compared with the other four protocols, OCO achieves 14% to 179% more throughput ratios. OCO also has 6% to 20% less energy consumption ratios. Furthermore, OCO is also implemented in a real testbed. The experimental results show that OCO achieves 31% to 75% more throughput ratios than compared schemes.

II. Related Work

In this section, related mcMACs for both WSNs and general wireless network are surveyed from two categories, namely, *synchronous* and *asynchronous*, respectively.

A. *Synchronous MAC Protocols*

Zhou *et al.* [2] proposed MMSN which is the first mcMAC that takes into account the restrictions imposed by WSNs. Senders in MMSN switch their current channels to channels of intended receivers at the beginning of every slot when they have packets to send. Kim *et al.* [3] proposed Y-MAC for WSNs where time is divided up into several fixed-length frames. The frames are composed of a broadcast period and a unicast period. The difference between Y-MAC and above mcMACs is that Y-MAC schedules receivers rather than senders to achieve low energy consumption. Salajegheh *et al.* [5] proposed HyMAC for WSNs where the communication period consists of a number of frames, which are divided up into scheduled slots and contention slots. The base station allocates specific time slots and channels to all nodes for communication. Jovanovic *et al.* [6] proposed TFMAC for WSNs where a frame consists of a contention period and a contention-free period that contains some equal sized time slots. It works similarly with HyMAC except that the schedules are made by all nodes rather than the base station.

In general wireless networks, mcMAC has also received a rapid growing interest in academia. So *et al.* [8] proposed MMAC for *ad hoc* networks by dividing up time into multiple slots, where all nodes exchange control information on the CC for reservations of DCs at the front of each slot and switch to DCs for data communication at the rest of the slot. Chen *et al.* [9] proposed MAP for *ad hoc* networks. MAP works in the same way to MMAC but has variable-size data time slots, so it avoids the problem that data slot has to be set according to the maximum data packet size. Tzamaloukas *et al.* [10] proposed CHAT for *ad hoc* networks using channel hopping scheme. Under CHAT, all idle nodes switch among all channels using a common hopping sequence. Moreover, both the sender and its receiver will stop hopping when they are aware of that they have to communicate with each other. Bahl *et al.* [11] proposed SSCH for *ad hoc* networks, which works in a different way to CHAT by adopting multiple hopping sequences for different nodes. Under SSCH, a data communication starts when two nodes hop on the same channel. Tzamaloukas *et al.* [12] proposed RICH-DP based on channel hopping for wireless networks, which differentiate itself with a receiver-initiated collision-avoidance scheme.

To sum up, above studies design protocols by time synchronization where let all control information or data be sent in some well-known slots and channels. For larger scale WSNs, however, synchronization itself remains an open issue and it is not completely solved on low cost sensor nodes with cheap faulty clocks that are prone to drift. One common solution is to send SYNC packets periodically, but these SYNC packets could induce considerable overhead, which consumes more energy and makes channels more crowded.

B. *Asynchronous MAC Protocols*

Wu *et al.* [13] proposed DCA for *ad hoc* networks, which uses two radios, one for control information exchanging and the other for data communication. Adya *et al.* [14] proposed MUP for wireless networks. MUP employs two radios like DCA, but it allows both radios to send control information and data interchangeably.

Above protocols are based on multi-radio scheme. Exploiting multi-radio can simplify the design of protocols by dedicating one radio on the CC to overhear the control information exchanging continuously. However, multi-radio schemes lead to not only larger node size but also more energy consumption. More importantly, increasing hardware cost makes the multi-radio schemes unrealistic for large scale WSNs.

Luo *et al.* [15] exploited Distributed Information SHaring mechanism (DISH) and proposed CAM-MAC for *ad hoc* networks. In CAM-MAC, when a node-pair performs a channel reservation on the CC, all neighbors may send cooperative packets to invalidate the reservation if they aware of that the selected DC or receiver is unavailable. Luo *et al.* [16] proposed ALTU based on altruistic cooperation, which introduces some specialized nodes called altruists whose only role is to acquire and share channel usage information.

These two mcMACs are based on DISH. Nevertheless, in every channel reservation, all the idle neighbors of the sender and its receiver will send packets for invalidation if they assume that this reservation is invalid. This scheme involves more packet transmission than necessary and easily results in cooperative packet collisions, since many cooperative packets could be sent simultaneously. Thereby, this scheme will consume considerable energy under large-scale WSNs context.

Le *et al.* [4] proposed PMC which utilizes a control theory approach to dynamically add available channel in a distributed method. In PMC, nodes work on current available channels by CSMA, and decide whether to switch to the next available channel based on certain parameters, which vary with channel utilization from time to time. However, computing methods of these parameters need further discussion. Sun *et al.* [17] proposed RI-MAC which is a receiver-initiated single-channel MAC protocol for WSNs. It attempts to minimize the time that a sender and its receiver occupy the wireless medium to find a rendezvous time for exchanging data. Wu *et al.* [7] proposed TMCP which is a multi-channel protocol that does not require time synchronization among nodes. However, this protocol is more like a topology control protocol than a MAC protocol. Zhou *et al.* [18] proposed CUMAC using cooperation for underwater WSNs, but it requires a tone device on each node to notify collisions, which increases the cost of WSNs.

C. *Summary*

From all mcMACs mentioned, it can be seen that currently there is no protocol that is based on *single-radio multi-channel asynchronous* MAC protocol *supporting duty cycling* for *WSNs*. Therefore, this paper proposes OMA, which addresses all these needs mentioned.

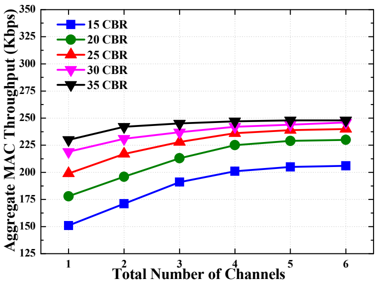


Figure 1. The simulation results for CCS verification

III. MOTIVTION

To bridge the growing gap between energy wastage due to the control packets collisions on the CC and limited availability of energy through fixed-budget batteries, this section identifies and verifies the source of the control packets collisions on the CC under multi-channel WSNs.

The Control Channel Saturation problem (**CCS**) means that under certain circumstances the CC is considered as a bottleneck of the network performance. Fig.1 shows how the CC becomes bottleneck, when the loads and the number of channels increase in the simulations. The mcMAC involved exploits a simple RTS and CTS handshake scheme on the CC to make the channel reservation, and then the sender and the receiver switch to the DC selected by the sender based on the overhearing on the CC. Finally, they communicate with each other on this DC. The specific detail of simulation setup is given in Section V.

It is observed that when the number of channels is larger than 4 and the number of CBR (Constant Bit Rate) are larger than 25, the throughput of mcMAC becomes *stable*, which is because the collisions on the CC become severer and thus it degrades the throughput. This is a clear indication that the CC becomes a bottleneck of the network performance. Therefore, if the CC is congested with retransmitted control packets, all the DC are prevented from fully utilized. Thereby, the spectrum resource is significantly wasted. This situation becomes even worse under duty cycle based WSNs where (1) the deployment density of nodes is usually higher than general wireless networks; (2) the traffic loads are usually bursty, and the senders usually wake up the sleeping receivers by continuously transmitting a series of handshake packets. Therefore, when the saturation situation occurs, many senders with data to transmit may resend control packets on the CC simultaneously, which make the CC more congested than it already is. All the DCs are also blocked from further utilization.

CCS is handled in this paper via an *opportunistic media access* scheme, which reduces the probability that multiple senders simultaneously transmit control packets on the CC. It is unwise to directly transmit all these control packets on the CC under WSNs context, since when the detected event occurs these control packets will quickly overwhelm the CC. This will significantly increase the collision probability of the control channels and degrade the network performance. This paper tackles the CCS with opportunistic media access.

IV. OMA PROTOCOL

In this section, before OMA is described in detail, two assumptions are made as follows. **(1)** Wireless bandwidth is divided into one dedicated Control Channel (CC) for control packets and K Data Channels (DC) for data packets. All channels have the same bandwidth and quality. Every pair of the channels are orthogonal to each other, so the packets simultaneously transmitted on different channels do not interfere with each other. All the nodes have prior knowledge of the frequencies of all the channels and the total number of DCs. **(2)** Each sensor node is equipped with a same single half duplex radio, which makes nodes can either send or listen on only one channel at a time but cannot do both actions simultaneously. In addition, the radio is capable of dynamically switching its channel.

As mentioned before, OMA relieves CCS with opportunistic media access to make a channel reservation for data transmission. The core of this scheme is to reduce the probability that multiple senders simultaneously transmit their control packets, *i.e*, handshake scheme, on the CC, which will degrade the performance of WSNs. For the sake of energy conservation, under OMA, when a transmission begins, a communicating node-pair transmits all the packets belonging to one message at one time serially, by DATA&ACK method. The details of media access of OMA are discussed in subsection A. Note that a sender *also receives* ACK packets from the receiver. Thus, a DC selected for data transmission has to be idle not only for the receiver but also for the sender. In this way, it does not work that a receiver checks the channel noise condition for notifying available DCs, which is usually employed in receiver-initiated schemes. In this work, we employ a random channel selection scheme for OMA, which is given in subsection B.

A. Media access scheme of OMA

An overview of the unicast scheme of OMA is as follows where a message transmission includes five steps as follows. **(1)** When the sender S in sleeping period has a message for the receiver R that is also in sleeping period, S wakes itself up, and then listens on the CC. **(2)** If the CC is idle, S first computes an opportunistic probability, denoted as p, based on the current network parameters (addressed in Section IV), and then accesses the CC with probability p or enters sleeping period with probability $1-p$ to make the handshake in the next active period. **(3)** If S chooses to access the CC, then S initiates a data transmission by sending a RTS packet on the CC including a DC number, say n, selected by S based on a certain scheme (discussed in the next subsection). **(4)** After receiving the RTS of the sender, R sends a CTS packet to confirm this transmission, and then switches to the DC_n. **(5)** ter S receives the CTS, S switches to the DC_n either, and then employs DATA&ACK method to commence the data transmission with R. Finally, they hop back to the CC to enter the sleeping period when this communication is over.

When S does not receive the CTS from R within a predetermined time interval after S sends out the RTS, S assumes that R is either on a DC for transmission or in sleeping period. Therefore, S wakes up R by a series of RTS until the predetermined RTS retry times is reached.

B. *Channel Selection Scheme of OMA*

When the sender S has data to transmit for the receiver R, S selects a DC based on certain channel selection scheme and then puts ID number of selected DC in the RTS. R should select the most likely idle DC based on some Channel Usage Information (CUI) that can be obtained by overhearing on the CC. This scheme is leveraged by the most of mcMACs in the literature.

However, there are several reasons why this overhearing based method is inefficient under multi-channel duty cycle based WSNs context. *Firstly*, since duty cycle scheme is the most efficient method to conserve energy, most of WSNs is based on duty cycle. Therefore, when a node under the duty cycle based WSNs is in sleeping period, it cannot overhear any control packet related to channel selection on the CC, which may lead to incomplete channel usage information. *Secondly*, in the single radio scenario, when a node is on a DC for communication, it cannot update its channel usage information in time either, which may also lead to an inaccurate selection of idle DC where other nodes probably are transmitting. This is problem also known as the multi-channel hidden terminals [8].

Based on above reasons, the overhearing based channel selection is inefficient under multi-channel duty cycle based WSNs. Thus, it is no better choice than the random selection when duty cycling as well as single-radio is employed and traffic loads are heavy. Thereby, to alleviate CCS, if not completely eliminate, OMA exploits random scheme to select DCs. By this scheme, when a node has data to transmit, it randomly selects a DC with probability q, and enters to sleep with probability $1-q$ to conserve energy. q equals the ratio of the average Available DCs number (denoted as k') over the current total available DCs number (denoted as $K-k$), which is thoroughly discussed in [19] where $K$and k are given, and k' is continuously varying according to some networks parameters. Due to the limit of space, the final formula of k' is not given in this work. Please check [19] for details.

C. *Handling CCS*

With opportunistic media access scheme and random channel selection, OMA is capable of greatly alleviating, if not completely eliminating, CCS. When a sender has data to transmit for the receiver, the sender has two opportunities to relief the CCS in the WSN. To begin with, the sender computes an opportunistic probability p according to the current conditions of networks, and then prepare to transmit control packets on the CC with probability p, or enters to sleeping period with probability $1-p$. Moreover, if the sender decides to transmit control packets for channel selection, the sender computes another probability q, and then actually transmit the control packets on the CC to the receiver with probability q, or backs off to enter the sleeping period with probability $1-q$.

Among the two opportunistic media accesses, the first opportunistic CC access is to avoid the collisions on the CC, while the second opportunistic DC access is to avoid the collisions on the DC. With these two opportunistic media accesses, not only can the transmitting node pairs efficiently alleviate the collisions on the CC that is the key issue we try to handle in this work, but also alleviate the collisions on the DC.

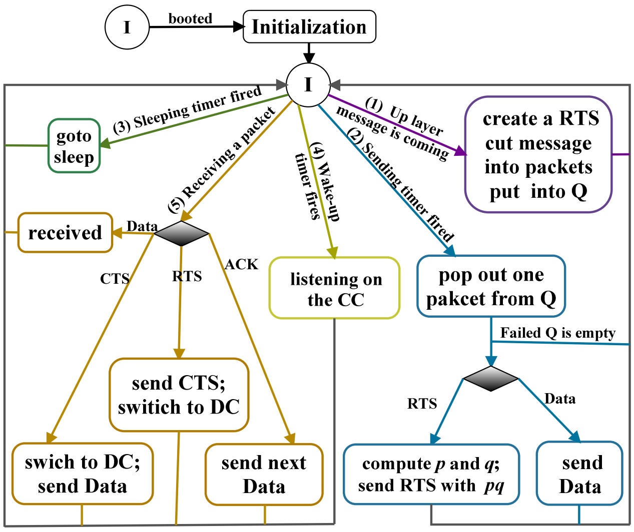


Figure 2. OMA node state machine

D. *Design of OMA*

The overall of OMA is captured by the node state machine shown in Fig.2. After every node boots up, it stays in the Idle state (I), and then it executes different actions according to the packets it received and the expirations of timers it set.

Under OMA, the specific changes of a node state are described as follows.

(1) When an upper layer message is coming: the node enters the message processing state. The node cuts the message into multiple data packets, and then creates a RTS and puts this *RTS* in front of data packets. Finally, the node puts RTS as well as data packets into a buffer queue Q.

(2) When a sending timer fires: the node enters the sending state. The node pops one packet from Q, if any, and treats this packet differently based on the type of this packet. If this packet is a data packet, then the node directly sends this packet. If this packet is a RTS, the node computes p and q, and then sends a randomly selected ID number of DC in a RTS with probability $p \cdot q$ or enters the sleeping period with $1-p \cdot q$.

(3) When a sleeping timer fires: the node turns its radio off and then enters to the sleeping period.

(4) When a wake-up timer fires: the node turns its radio on and then enters to the wake-up period and listens on the CC to receive incoming RTS packets.

(5) When the node receives a packet: the node enters to the receiving state. If the packet received by the node is a data packet, the node directly relays this packet to the upper layer; if the packet is a RTS intended for it, the node sends a CTS and then switches to the DC with the ID number n included in this RTS; if the packet is a CTS intended for it, the node switches to the DC it selected, and then sends a DATA to the receiver; if the packet is an ACK, then the node sends the next data packets, if any, to the receiver.

V. PERFORMANCE ANALYSIS

In this section, we make a theoretical analysis for the performance of OMA. In particular, we compute the opportunistic probability p with which the senders transmit the control packets on the CC when the senders have data packets to transmit. Under OMA, the probability p ensures that during the time interval of one control packet transmission, the expected number of control packets transmitting on the CC is equal to or less than 1. Therefore, OMA can greatly alleviate collisions between control packets on the CC, and thus conserve more energy to extend the lifetime of WSNs.

Assume that the packet arrival process is Poisson arrival process. Let T_0 be a sufficiently long time interval. During T_0, the total Number of Arrival Messages at each node, denoted as NAM, is given by

$$NAM = \frac{\lambda T_0}{AVG}, \tag{1}$$

where λ is the average data packet arrival rate at a node, and AVG is the average number of data packets in a message (*i.e.*, segment). Therefore, the total Time that a node Sends all these Messages on DCs, denoted as TSM, is given by

$$TSM = T_{\mathrm{DC}} \cdot \frac{\lambda T_0}{AVG}, \tag{2}$$

where T_{DC} is the average duration length of one message communication on a DC, which consists of multiple data packet transmissions.

On the other hand, approximately, the Total time that a node Receives all the Messages, denoted as TRM, is given by

$$TRM = p_{rcv} \cdot (1 - p_{cc} - p_{slp}) \cdot T_0, \tag{3}$$

where p_{rcv} is the probability that a node switches to a DC as a receiver, p_{cc} is the probability that a node is on the CC at an arbitrary time, and p_{slp} is the probability that a node is sleeping at an arbitrary time.

In the long run, the total time that a node sends messages is supposed to equal the total time that a node receives these messages, when the networks is stable (*i.e.*, after sufficiently long time). Therefore, via (2) and (3), we have

$$T_{\mathrm{DC}} \cdot \frac{\lambda T_0}{AVG} = p_{rcv} \cdot (1 - p_{cc} - p_{slp}) \cdot T_0. \tag{4}$$

Assuming that $p_{rcv} = 1/2$ in the long run, we have

$$p_{cc} = 1 - p_{slp} - \frac{2\lambda T_{DC}}{AVG}. \tag{5}$$

The duty cycle, denoted by q, is given by the design of protocols, and is defined as the awake idle listening time on the CC (denoted by T_{idle}) over the awake idle time on the CC plus sleeping time (denoted by T_{sleep}), *i.e.*,

$$q = \frac{T_{idle}}{T_{idle} + T_{sleep}}. \tag{6}$$

We transform (6) into

$$q = \frac{T_{idle}/T}{T_{idle}/T + T_{sleep}/T}. \tag{7}$$

If we assume T is an appropriate length of time, we have

$$q \approx \frac{p_{idle}}{p_{idle} + p_{slp}}. \tag{8}$$

where p_{idle} is the probability that a node is idle on the CC at an arbitrary time. Moreover, via (8), we have

$$q = \frac{1}{1 + p_{slp}/p_{idle}} < \frac{1}{p_{slp}/p_{idle}} = \frac{p_{idle}}{p_{slp}}. \tag{9}$$

Because the situation that a node is on the CC includes two cases (*i.e.*, *first*, it is idle on the CC; *second*, it is exchanging control packets on the CC), we have

$$p_{idle} < p_{cc}. \tag{10}$$

Therefore, via (9) and (10), we have

$$q < \frac{p_{idle}}{p_{slp}} < \frac{p_{cc}}{p_{slp}}. \tag{11}$$

Via (5) and (11), we have

$$p_{cc} > \frac{1 - 2\lambda T_{DC}/AVG}{1 + 1/q}. \tag{12}$$

Therefore, in the long run, the Expected Number of any node's neighbors that on the CC, denoted as ENC, is given by

$$ENC = N \cdot p_{cc} > N \cdot \frac{1 - 2\lambda T_{DC}/AVG}{1 + 1/q}. \tag{13}$$

where N is the average number of neighbors of a receiver, *i.e.*, network density.

Therefore, according to the Poisson arrival process, during the time interval T_{ctl} of one control packet transmission, the probability p' that no message is arrival at all the neighbors of a sender is given by

$$p' = \frac{e^{-ENC \cdot \lambda \cdot T_{ctl}} \cdot (ENC \cdot \lambda \cdot T_{ctl})^0}{0!} = e^{-ENC \cdot \lambda \cdot T_{ctl}}. \tag{14}$$

Therefore, the upper bound of opportunistic probability p, denoted as p^*, with which a sender on the CC may send a control packet is given by

$$p^* = \min(1, p') < \min(1, e^{-\frac{(1+1/q)\cdot\lambda\cdot T_{ctl}}{N\cdot(1-2\lambda T_{DC}/AVG)}}). \tag{15}$$

During every data transmission, all the senders on the CC *uniformly* choose p in interval $(0, p^*)$, and opportunistically send an control packet with probability p or back off to enter the sleeping period with probability $1 - p$. Therefore, the expected number of control packets sent by all the senders on the CC with opportunistic probability is equal to or less than 1. Note that N and q can be set according to the network deployment; λ can be obtained by a packet counter in the MAC layer; and T_{DC}, T_{ctl} as well as AVG can be real-time estimated by a progressive weighted method. Therefore, p is solvable and is dynamically adaptive according the network parameters.

VI. Performance Evaluation

In this section, we performed both simulations and real testbed experiments to evaluate the performance of OMA.

A. Simulation Results

We implemented a simulator using C++, which has 289 nodes whose transmission ranges are set to 40m. The nodes are uniformly deployed in a square area of size $200\text{m} \times 200\text{m}$ with a node density of 38 (*i.e.*, a node that is not in the edge of networks has 37 neighbors). The many-to-many transmission model is used where the payload size is set to 32 Bytes and the channel bandwidth is set to 250 Kbps.

To investigate the effect of opportunistic media access, OMA is compared with another four famous schemes: (1) CSMA\CA is a classic single channel MAC protocol; (2) MMSN [2] is a typical synchronous mcMAC with a static channel selection; (3) PMC [4] is an asynchronous mcMAC with a dynamic channel selection; (4) CAM-MAC [15] is a synchronous mcMAC with DISH. Moreover, two varieties of OMA are also implemented for comparisons. The first one utilizes Consistent Media access, called CMA, which directly access the CC and is used to justify the effect of opportunistic media access. The second one exploits a Fixed probability of 50% based Media Access, called FMA, which is used to justify the effect of opportunistic probability.

Four groups of simulations are conducted to examine four metrics as follows: throughput, packet delivery ratio, communication latency and energy consumption. In each group, different Total Number of Channels (**TNC**) and the network loads are considered. The total number of channels includes the CC and all the DCs, and the network loads are varied via changes of the Number of CBR (**NCBR**, Constant Bit Rate) streams in the network. In all simulation experiments, TNC is set to 4 when NCBR is varying, while NCBR is set to 30 when different TNCs are exploited in the simulations p.

1) Evaluation on throughput: The throughput is computed as the total amount of all useful data packets successful delivered via the MAC layer of the networks per unit time.

The effect of the total number of channels on throughput is shown in Fig.3 (a). Compared with others, OMA has lower throughput when the total number of channels is small than 4. Beside the duty cycling, this is also because OMA uses the two-way handshake and opportunistic media access, which will pay considerable cost if the total number of channels is relatively small. When more channels are available, OMA, CAM-MAC and PMC allow more nodes to simultaneously communicate on different DCs. This is because they employ dynamic channel selections, and thus outperform CSMA\CA and MMSN. However, when the total number of channels becomes larger, OMA performs better than CAM-MAC and PMC. This is because CAM-MAC suffers from collisions of cooperative packets and PMC suffers from CCS, whereas OMA avoids using cooperative scheme and tackles CCS by opportunistic media access, so it achieves higher throughput. Moreover, OMA outperforms CMA and FMA due to its opportunistic scheme, which avoids the collisions on the CC.

The effect of loads on throughput is shown in Fig.3 (b). It is observed that the throughputs of all the protocols rise with the number of CBR streams. This is due to the fact that if more node-pairs are involved in data communications, more parallel transmissions will occur on the DCs. Under light loads, OMA is suboptimal to other protocols. Nevertheless, the results show that under heavy loads OMA performs progressively better than other protocols. This indicates that even though OMA is duty cycling, OMA still significantly benefits from opportunistic media access when CCS becomes more serious with the rise of the loads. Again, OMA outweighs CMA and PMA when loads are heavy.

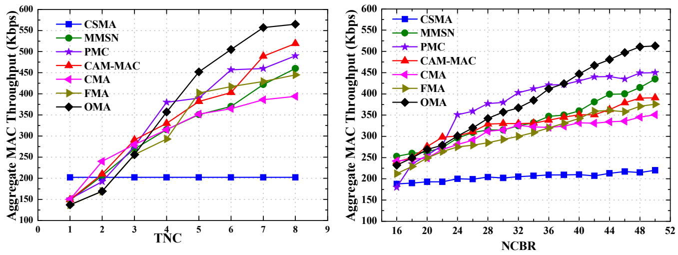
2) Evaluation on packet delivery ratio: Packet delivery ratio is computed as the ratio of the total number of packets that MAC layer successful delivered over the total number of packets that the upper-layer requests MAC layer to deliver.

The effect of the total number of channels on packet delivery ratio (PDR) is shown in Fig.4 (a). The results show that all the packet delivery ratios increase with the rise of the total number of channels. When the total number of channels is smaller than 4, MMSN and PMC achieve better performances than CAM-MAC and OMA. One reason is that cooperative schemes of CAM-MAC and opportunistic media access of OMA undermine packet delivery ratio. However, when the total number of channels is larger than 5, OMA outperforms others, but CMA and PMA still perform worse than MMSN, and PMC. This is because OMA involves fewer collisions on the CC. In addition, CMA has many collisions due to its consistent media access and PMA does not consider the current status of the networks and backs off with a fixed probability.

The effect of loads on packet delivery ratio is shown in Fig.4 (b). It is observed that all the packet delivery ratios decrease when the loads are heavier except that of OMA-50%, which maintains stable around 96%-97%. This is because in opportunistic media access, node-pairs more likely to avoid the collisions on the CC, so they can find a DC for communication in time. Moreover, PMA outperforms CMA, which verifies values of backoff schemes. MMSN and PMC outperform PMA and CMA, which is still due to the fixed probability to access media and the flaws of consistent media access. Note that CAM-MAC has a lower packet delivery ratio than all the protocols due to CCS, which causes the situation that the collisions on the CC between reservation packets and cooperative packets become more serious when loads are heavier.

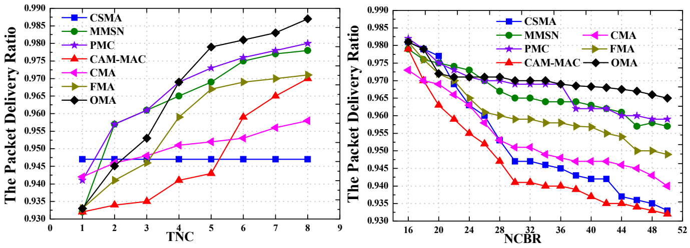
3) Evaluation on latency: The communication latency reflects the time delay from the time instance that a data packet from the upper layer is delivered to the MAC layer to the time instance that this packet is successfully sent out.

The effect of the total number of channels on latency is shown in Fig.5 (a). The results indicate that compared with others, OMA has larger latency when the total number of channels is smaller than 3. However, as it increasingly steps up, the difference on latency becomes negligible since other protocols suffer the retransmission problem resulted from CCS, which is effectively handled by opportunistic media access in



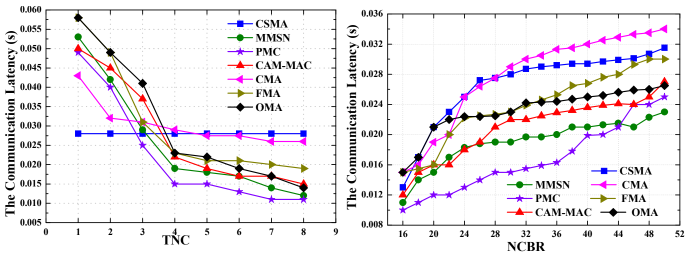
(a)Throughput vs. Total Number of Channels (b) Throughput vs. Loads

Figure 3. Throughput evaluation



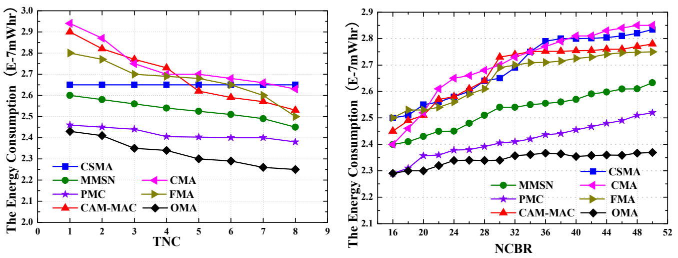
(a) PDR vs. Total Number of Channels (b) PDR vs. Loads

Figure 4. Packet delivery ratio evaluation



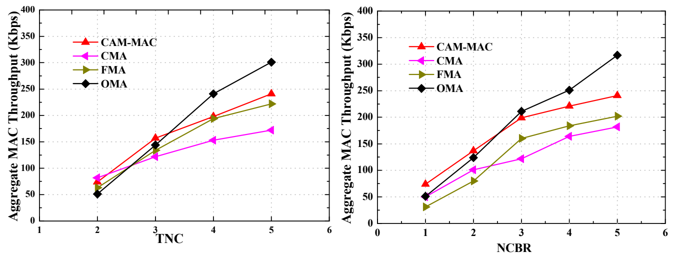
(a) Latency vs. Total Number of Channels (b) Latency vs. Loads

Figure 5. Latency evaluation



(a) Energy vs. Total Number of Channels (b) Energy vs. Loads

Figure 6. Energy consumption evaluation



(a) Throughput vs. Total Number of Channels (b) Throughput vs. Loads

Figure 7. Testbed evaluation on throughput

OMA. CMA has a low latency when the total number of channels is smaller than 3, while has a high latency when the total number of channels is bigger than 4. This is because when the number of channel is small, CCS is less critical; whereas when the number is becoming larger, CCS greatly undermines the transmission under consistent media access.

The effect of loads on latency is shown in Fig.5 (b). It is observed that when the network loads are light, OMA has a larger latency than other protocols. However, when CCS becomes more severe as the loads are heavier, the gap between OMA and other protocols on latency becomes narrower. This is mainly because OMA effectively addresses CCS. Moreover, CMA involves larger latency than OMA as expected, and PMA also has a larger latency due to that fixed probability based media access results in many collisions on the CC. MMSN and CAM-MAC achieve greatly lower latency than OMA when the network loads is light. This is also due to that when the loads are small, CCS cannot significantly affect the transmissions under them. PMC achieves the lowest latency until the number of CBR streams is larger than 44. Nevertheless, the gap on latency between OMA and other protocols is negligible when the number of CBR streams is larger.

***4) Evaluation on Energy Consumption*:** In this study, the energy consumption for all the protocols is computed as the energy consumed to successfully deliver a useful data byte.

The effect of the total number of channels on energy consumption is shown in Fig.6 (a). The results show that energy consumptions of all the protocols decrease with the rise of the total number of channels, but OMA outperforms others all the time due to its effective opportunistic media access to handle CCS. All the results indicate that OMA can conserve more energy to prolong the lifetime of WSNs by its duty cycle scheme and effective solution to CCS. Note that CMA consumes more energy than others due to that its consistent media access needs more energy to handle the collisions on the CC caused by CCS. In addition, CAM-MAC consumes higher energy than others due to its collisions of cooperative packets, which undermines many communications when CCS is more serious. Note that when the total number of channels is becoming larger, the gap between OMA and PMA on energy consumption is becoming larger. This may indicates that OMA with opportunistic media access is capable of achieving higher energy efficiency under the networks with more DCs.

The effect of the loads on energy consumption is shown in Fig.6 (b). All the energy consumptions increase when the loads rise. OMA maintains a relatively low energy consumption since opportunistic media access reduces the probability of control packet collisions. Whereas other protocols suffer from certain problems: MMSN consumes more energy to maintain time synchronization; PMC has many collisions on the current channel when the loads are heavy; and CAM-MAC, PMA as well as CMA still suffer from retransmissions resulted by CCS and then consume more energy than other protocols.

(a) Hawk node (b) A snapshot in the testbed experiment

Figure 8. Testbed experiments

B. Testbed Results

We built a sensor node platform, Hawk, to evaluate the performance of OMA. Hawk employs μC/OS, where each node is equipped with an nRF905 radio and a MSP430 processor. A hawk node is shown in Fig.8 (a). The testbed consists of 10 hawk nodes which are completely connected as shown in Fig.8 (b). Thereby, all the nodes are within communication range of each other, similar to the work in [15]. The size of each packet is 32 Byte, and data transmission rate is 100 Kbps. All the nodes randomly choose a neighbor to transmit. The experiment was repeated for 10 times. When an experiment is finished, all nodes send their total number of bytes received during the experiment to a sink, which is connected to a desktop computer, and thus throughput can be obtained. Due to the time synchronization of MMSN and the complexity of PMC for parameter computations, only OMA, PMA, CMA and CAM-MAC were implemented for throughput comparisons.

When the number of CBR is set to 5, the effect of the total number of channels on throughput is shown in Fig.7 (a). It is observed that CAM-MAC has higher throughput than OMA, when the total number of channels is less than or equal to 3. CAM-MAC does not have to back off when the nodes have packets to send, and the backoff compromises the throughput of OMA when CCS is less serious. However, OMA achieves better throughput as total number of channels is larger than or equal to 4. This is because when more DCs are available, CCS becomes more serious, and OMA tackles it with less cost than CAM-MAC. In addition, OMA has similar or little lower throughput compared with CMA and PMA when the total number of channels is small, while OMA outperforms them when TNC is larger than 3. These results are roughly consistent with the simulation comparisons shown in Fig.3 (a), which further justifies the value of opportunistic media access.

When the total number of channels is set to 5, the effect of loads on throughput is shown in Fig.7 (b). It shows that OMA and its two varieties have lower throughput than CAM-MAC when loads are light. This is because when fewer nodes are communicating, the cooperative scheme of CAM-MAC works better than opportunistic media access of OMA. However, when loads are heavy, the collisions on the CC become more serious. Therefore, OMA outperforms CAM-MAC when the loads are heavy. Note that OMA performs better than PMA and CMA all the time. Once again, these results are generally consistent with the simulation results shown in Fig.3 (b), which shows that opportunistic media access actually improves the throughput of OMA.

VII. CONCLUSION

Control channel saturation problem is a major cause of energy wastage in multi-hop multi-channel duty cycle based WSNs. To address this problem, in this paper, a multi-channel duty cycle based MAC protocol called OMA is proposed. OMA exploits opportunistic media access to efficiently handle control channel saturation problem. Being fully distributed with no requirements of time synchronization or multi-radio, OMA is very easy to be implemented in resource-constrained sensor nodes. In theoretical analysis, this paper obtains the opportunistic probability, which can guide configurations of OMA. Moreover, extensive simulations were conducted to examine the performance of OMA. The results show that with opportunistic probability, OMA can handle control channel saturation with a lower cost, and still enable duty cycling at the same time. Thereby, OMA achieves a significant improvement in the energy efficiency and other performances as well, especially when the total number of channels and loads increase. We also implemented OMA on a real sensor platform. The results show that opportunistic media access actually enables OMA to achieve better throughput.

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