M&M: a Multi-Channel MAC Protocol with Multiple Channel Reservation for Wireless Sensor Networks

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Abstract—**In this paper, a multi-channel MAC protocol, called M&M, with multiple channel reservation is proposed to tackle the channel conflict problem. M&M is fully distributed with no requirements of time synchronization or multi-radio, so it is very practical to implement M&M in resource-constrained sensor nodes. M&M can make nodes to choose one actually idle channel for communications from all assumed idle channels. Therefore, M&M can greatly alleviate, if not completely eliminate, packet collisions resulted by the channel conflict, and thus conserve more energy to prolong the lifetime of WSNs. To investigate the values of multiple channel reservation, extensive simulation and real testbed experiments are conducted. The results show that when the number of channels becomes larger or loads are heavy, M&M improves energy efficiency and throughput significantly.**

I. INTRODUCTION

Recently, to remedy drawbacks of single-channel MAC protocols, some multi-channel MAC protocols (**mcMAC**) have been proposed to support applications [1][2][3] of WSNs via parallel transmissions, e.g., MMSN[4], Y-MAC[5], PMC[6]. They have several advantages. *First*, because 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, multiple transmissions can simultaneously be commenced on different DCs. Therefore, mcMACs have higher throughput and shorter latency. *Third*, because current off-the-shelf WSNs radios such as CC2420 already offer multiple channels [4], mcMACs involve no multi-radio hardware cost.

A mcMAC generally consists of channel selection and media access. The channel selection decides how to select idle channels for nodes in order to optimize performance of WSNs; whereas the media access decides when and how nodes access the channels that have been selected for them. According to how frequently channel selection schemes are performed, channel selection schemes can be generally classified as *static* and *dynamic*. Under static schemes [4], every node chooses its own dedicated channel to receive data, and switches to other channels to send data. To avoid collisions, static schemes have to guarantee to select different channels for different nodes within two-hop neighborhood, so the number of channels required in static schemes is *at least* as large as the number of two-hop nodes. To remedy this drawback, dynamic schemes [6][7] dynamically select channels for communicating node-pairs on demand. Therefore, channels are occupied by busy node-pairs only. Thus, the number of channels required in dynamic schemes is *at most* half of the number of two-hop nodes plus the number of Control Channel (**CC**), which is typically set to 1 and is used to reserve Data Channels (**DC**).

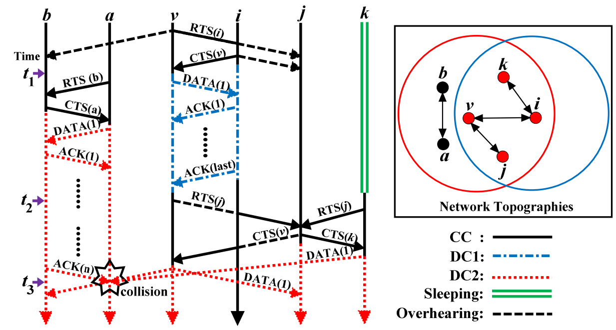

Figure 1. The illustration of channel conflict problem

Based on the scheme used to access media, existing media access schemes generally fall in two basic categories: *Time Division Multiple Access* (*TDMA*) and *Carrier Sense Multiple Access* (*CSMA*). In TDMA [4][5][8][9][17], time is divided up into discrete time slots, which have equal or unequal lengths based on different protocols. The time slots are allocated to all nodes in the network where nodes are scheduled to send or to receive packets based on different schemes. However, TDMA usually requires tight time synchronization, which involves considerable overhead. Whereas, in CSMA [6][7][11][15][16], all nodes poll channels when they are idle, and initiate a handshake with their receivers when they have packets to send. This scheme is a natural way for nodes to access shared media. Nevertheless, CSMA will bring more collisions than TDMA since all nodes in the network can begin to transmit packets simultaneously due to their contention nature.

Dynamic channel selection and CSMA with duty cycling are jointly considered as suitable schemes for WSNs because: (1) dynamic channel selection requires a smaller number of channels than static schemes; (2) CSMA involves no overhead of time synchronization in TDMA; (3) duty cycling periodically turns off the radio of idle node to prolong the lifetime of WSNs. However, these combined schemes sometimes fail to offer satisfactory performances due to Channel Conflict Problem (**CCP**). As shown in [7], CCP is one of the most significant sources of energy wastages in the multi-channel scenario. CCP results from that the usage information of a channel may not be timely obtained by all nodes. Therefore, when a node selects an Assumed Idle DC (**AIDC**) for data communication, this AIDC may be already being used by other nodes. The AIDC that is actually busy is called the Misunderstood Channel (**MC**).

An illustration of CCP is given in Fig.1. It involves one CC and two idle DCs. Node a, b, v, i, and j are active and k is sleeping. When v has data for i, v randomly selects an idle DC such as DC_1 and puts reservation information (e.g., who will

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occupy which channel for how long) into a RTS sent to i on the CC. Then, i sends a CTS back to v to confirm this RTS. Next, v and i switch their channels to DC_1 around time t_1. The active neighbors of v and i (e.g., a, b and j) update their channel usage information by overhearing on the CC, whereas the sleeping neighbors (e.g., k) still assume that DC_1 is idle. During $(t_1,\ t_2)$, a has data for b. a randomly selects an idle DC such as DC_2 and then switches to DC_2 with b after a reservation. Because v and i are not overhearing on the CC as well as k during $(t_1,\ t_2)$, v, i and k still assume that DC_2 is idle. Around t_3, two situations could create a CCP. (1) When v finishes sending data to i, v has data for j. If v also selects DC_2 that a and b are still occupying, then a CCP is created. (2) When k wakes up, k has data for j. If k also selects DC_2 that a and b are still occupying, then a CCP is created too. Both of these two CCPs could cause packet collision in a or b around t_3.

Aiming at solving CCP, this paper proposes a duty cycle based asynchronous Multi-channel MAC protocol with Multiple channel reservation for higher data rate applications in WSNs, called M&M. Although WSNs were initially motivated by light loads applications, new applications demanding higher throughput quickly emerged after few years, e.g., wireless multimedia sensor networks. The key novelty of this paper is that under M&M, instead of reserving only one AIDC, the sender and its receiver decide a list of AIDCs together and then communicate on one actual idle channel on that list. Therefore, M&M can greatly alleviate, if not eliminate, THT to conserve more energy for prolonging the lifetime of WSNs.

This paper hopes to contribute in the following ways. (1) To the best of authors' knowledge, this paper makes the first attempt to apply the idea of multiple channel reservation to solve CCP in WSNs. (2) An asynchronous mcMAC, called M&M, is presented especially for higher loads applications under WSNs, which achieves energy efficiency by duty cycling. (3) Extensive simulations are conducted to evaluate the performance of M&M compared with other four protocols. (4) More importantly, M&M is implemented in a real testbed and lessons learned in the implementation are shared.

The rest of this paper is organized as follows. Section II examines the existing mcMAC. Section III describes the design of M&M. In section IV, both simulation and real testbed experiments are conducted to evaluate M&M. Finally, Section V summarizes the work and presents conclusions.

II. Related Work

This work is related to both mcMACs for WSNs and current solutions for CCP in generally wireless networks, respectively.

A. Existing mcMACs for WSNs

In this paper, mcMACs for WSNs are surveyed from two main categories, namely: *synchronous* and *asynchronous*.

1) *Synchronous mcMACs for WSMs*: Zhou *et al*. [4] propose MMSN which is the first mcMAC that takes into account the restrictions in WSNs. By four kind of static channel selections, senders in MMSN switch their current channels to channels of receivers at the beginning of every time slot when they have packets to send. Nevertheless, static channel selections not only limit channel utilization but also are prone to bring more multi-channel hidden terminals. Salajegheh *et al*. [8] propose HyMAC where the communication period consists of a number of frames. The base station selects channels and specific frames to all nodes. Jovanovic *et al*. [9] propose TFMAC where a frame consists of a contention period and a contention-free period that contains some equal sized time slots. TFMAC works similarly with HyMAC except that the schedules are made by all nodes rather than the base station. Kim *et al*. [5] propose Y-MAC via adding a multi-channel mechanism to Crankshaft [10]. The difference between Y-MAC and other synchronous mcMAC is that Y-MAC schedules receivers rather than senders to achieve low energy consumption.

2) *Asynchronous mcMACs for WSNs*: Le *et al*. [6] propose PMC where nodes work on current available channels by CSMA, and decide whether to switch to the next available channel based on certain parameters, which vary from time to time based on channel utilization. However, the computing method of these parameters needs further discussions. Wu *et al*. [11] propose TMCP which is a multi-channel protocol that does not require time synchronization. However, this protocol is more like a topology control protocol rather than a MAC protocol. Ansari *et al*. [12] propose a spectrum agile MAC protocol where all nodes scan all channels and make sure whether there are packets for themselves, which may involve a considerable overhead of channel switching. Zhou *et al.* [24] present CUMAC using cooperation for underwater WSNs, but it requires a tone device on each node to notify collisions, which significantly increases the cost for WSNs deployment.

B. Current Solutions for CCP

The current solutions for CCP in wireless networks can be generally categorized into three classes: *multi-radio scheme*, *time synchronization* and *distributed information sharing*.

1) *Multi-Radio Scheme*: Wu *et al*. [13] propose DCA which uses two radios, one for control information exchanging, and the other for data communication in ad hoc networks. Adya *et al*. [14] propose MUP which employs two radios like DCA, but MUP allows both radios to interchangeably send control information and data. Jain *et al*. [15] propose a protocol with a dedicated radio for control information exchanging, but it utilizes a receiver-based channel selection scheme via SNR comparisons at receivers. Nasipuri *et al*. [16] propose a multi-radio protocol which distinguishes itself by a soft channel reservation scheme as it gives preference to the channel that is used for the last successful communication.

To sum up, using multi-radio can solve CCP by dedicating a radio on the CC to consistently overhear control information exchanging. In this way, all the channel usage information from neighbors is available to any node. However, the requirement of multi-radio leads to not only larger node size but also more potentially energy consumption [7], which could result in a shorter lifetime of WSNs. More importantly, increasing hardware cost of radios makes it unrealistic for large-scale WSNs.

2) *Time Synchronization*: So *et al*. [17] propose MMAC which partitions time into multiple slots. In MMAC, all nodes exchange control information on the CC for channel reservations in the front of each slot and switch to DCs for communications in the rest of the slot. Chen *et al*. [18] propose MAP which works in the same way to MMAC but has variable-size data slots. Thereby, MAP avoids the problem that data slot has to be set according to the maximum data packet size. Tzamaloukas *et al*. [19] propose CHAT which employs time synchronization in channel hopping scheme. Under CHAT, all idle nodes switch among all channels using a common hopping sequence. Bahl *et al*. [20] propose SSCH that is also based on the channel hopping, but SSCH uses multiple hopping sequences for different nodes.

In summary, these studies address CCP by time synchronization where mostly let all the control information (i.e., channel reservation information) be sent in some well-known time slots and channels. However, time synchronization itself remains a major issue that is not completely solved on low cost sensor nodes with cheap faulty clocks that are prone to drift [11]. One common solution is to periodically send SYNC packets, but it will consume more energy and make channels more crowded.

3) *Distributed Information Sharing*: Luo *et al*. [7] take advantage of Distributed Information SHaring mechanism (DISH) and propose CAM-MAC to address the multi-channel coordination problem for ad hoc networks. In CAM-MAC, when a communicating 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 is unavailable. In addition, Luo *et al*. [21] propose a mcMAC based on a strategy called altruistic cooperation. This protocol introduces some specialized nodes called altruists in the network whose only role is to acquire and share channel usage information. Furthermore, Luo *et al*. [22] develop a theoretical treatment of DISH to analytically evaluate the availability of information sharing. Instead of directly analyzing throughput, this study analyzes the availability of information sharing and correlates it with performance metrics including throughput.

In short, DISH solves CCP by involving more nodes into a channel selection. However, in every channel reservation, all the idle neighbors of the sender and the receiver will send packets for invalidation, if they assume this reservation is invalid. It involves more packets sending than necessary and easily results in cooperative packet collisions, because many cooperative packets could be sent simultaneously. Therefore, DISH will consume considerable energy in large-scale WSNs.

C. Summary

In this paper, M&M is proposed for WSNs to tackle CCP in a distinct way. Three salient features distinguish M&M from prior work. *Firstly*, under M&M nodes are only equipped with one single radio; *secondly*, M&M is fully asynchronous; *thirdly*, all communicating node-pairs under M&M make channel selection decision based only on themselves, i.e., no extra nodes are involved for data communication.

III. Design Of M&M

Before M&M is described in detail, assumptions are made as follows. (1) Wireless bandwidth is equally divided into one dedicated CC for control packet exchanging and K DCs for data communication, and all nodes have a prior knowledge of the frequencies of all channels and the total number of DCs. In addition, every channel is orthogonal to the others, so the packets simultaneously sent on different channels do not interfere with each other. (2) Each sensor is equipped with a same single switchable half-duplex radio. (3) Retransmission is not considered in M&M, and every node is aware of two hop neighbor information.

A. *Overview of M&M*

M&M is a duty cycle based asynchronous mcMAC with multiple channel reservation. Three features of M&M are described as following. *Firstly*, M&M utilizes a sender centric coordination to wake up its receiver by a series of handshake packets (RTS) according to the duty cycle. In addition, each idle node periodically turns its radio on and off based on its own duty cycle to conserve energy and to prolong the lifetime of WSNs. *Secondly*, the independent sleeping schedule of each node reflects the asynchronization of M&M. *Thirdly*, under M&M, every node-pair reserves multiple AIDCs instead of one.

Under M&M, all nodes take four actions as follows. **(1) Overhearing**: When an active node is idle, it monitors the CC to overhear control information exchanging to update its Channel Usage Information (**CUI**) for next channel reservation. **(2) Reserving**: When it has packets to send, it uses a handshake scheme with its receiver on the CC to negotiate a list of common AIDCs for data communication. **(3) Communicating**: After reserving, this node and its receiver employ media access scheme for communication on one of all the DCs they reserved. **(4) Duty cycling**: When being idle for a certain length of time decided by the duty cycle, this node turns off its radio and enters sleeping period for a certain length of time, which also decided by the duty cycle.

B. *Channel Selection of M&M*

The channel selection of M&M is a dynamic scheme, and its objective is to avoid CCP. Channel selection schemes in other mcMACs try to update the CUI in real-time, which is the main idea of current solutions for CCP. As shown before, this will involve too much time synchronization overhead or hardware cost (e.g., multi-radio). In this study, CCP is handled from a new aspect. Specifically, instead of being updated in real-time, these outdated CUI could be appropriately used to tackle CCP. The outdated CUI has a property as follows: if the outdated CUI shows that a DC is *idle* now, then this DC is *probably idle*, whereas, if the outdated CUI shows that a DC is *busy* now, then this DC is *definitely busy*.

As shown in Fig.1, this property is resulted by that a node misses some control information during its sleeping period or communications on a DC. This property is utilized in M&M to

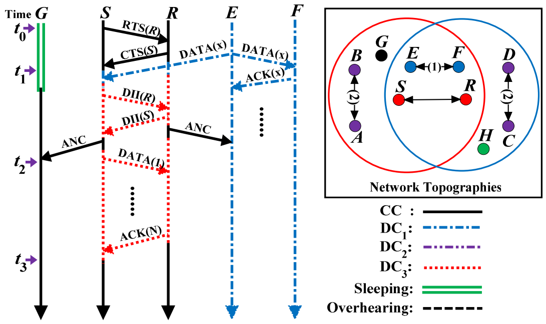


Figure 2. The Illustration Of M&M

design a channel selection scheme, called multiple channel reservation. When a sender has packets to send, it uses this property to obtain the DCs that its CUI assumes they are idle, but they are *probably* busy. Next, this sender makes these AIDCs into a list, called AIDC List (***AIDCL***), and then sends *AIDCL* to its receiver. When this *AIDCL* is received, its receiver does the same actions to obtain its *AIDCL*, and computes the intersection of *AIDCL*s, called Final *AIDCL*(***FAIDCL***), and finally sends *FAIDCL* back to the sender. After that, both the sender and its receiver switch among all the DCs in *FAIDCL* based on the random order of channels in *FAIDCL* until they find an actually idle DC. When they find an actually idle DC, they have to switch back to the CC first and inform all idle neighbors that they actually use this DC instead of other DCs in *FAIDCL*. Therefore, all these idle neighbors could update their CUI.

In M&M, a node-pair reserving multiple AIDCs instead of one is because if they reserve one AIDC and this DC is actually busy, they have to switch back to the CC and reserve a new AIDC again via another handshake. Moreover, this new AIDC could also be busy. Therefore, reserving only one AIDC at once could result in multiple handshakes on the CC for one message communication that consists of multiple data packet communications. These multiple handshakes undermine the utilization of the CC and consume more energy than necessary.

C. Media Access of M&M

Three new kinds of packet are included in CSMA-based M&M, which are ***CSC*** (used to inform a node on a DC that it needs to Continue to Switch Channel among *FAIDCL*), ***DII*** (used to inform a node on a DC that this DC Is Idle, which mainly tackles the multi-hop hidden terminals) and ***ANC*** (used to make an ANnounCement on the CC about the DC a node actually uses). The media access of M&M is given in Algorithm 1 where *S* and *R* represent a sender and its receiver. In M&M, a node-pair precedes an actually message communication phase (*DATAs*/*ACKs*) with a handshake phase (*RTS*/*CTS*) and a channel announcement phase (*DII*/*CCS*/*ANC*). It is worth noting that *ACK* being involved indicates senders also are supposed to *receive ACK*s in M&M, so the DC selected must be idle for both the sender and its receiver. The handshake is used to negotiate a list of AIDCs by this node-pair, while the channel announcement is to select an actually idle DC in *FAIDCL* and to help all their idle neighbors correctly update their CUIs.

Algorithm 1: Media Access of M&M

```
If (upper layer message coming) { put message into packet buffer queue;};
If (sleeping timer fired) { turn off radio; set up active timer by duty cycle;};
If (active timer fired)     { turn on radio; set up sleeping timer by duty cycle;};
If (sending timer fired){
  check whether R is on the DC by CUI; use CCA to sense the CC;
  If (R is on DC || CC is busy){
    back off for a while and tries to send later;}
  Else {obtain AIDCL by CUI; send it in RTS to R;}};
If (receiving a packet){
  If (packet is RTS){ // as a receiver
    obtain AIDCL by CUI; obtain FAIDCL; send it in CTS to S;
    While (switch to next DC in FAIDCL){
          monitor this DC for 2T(explain later in subsection III.D);
          If (this DC is busy){
                If (node occupying this DC is not a neighbor of S ){
                 send CSC on this DC  to inform S to switch again;}}
          Else If (receiving the DII packet from S){
                send DII on this DC to S; switch to the CC;
                inform neighbors which DC it occupied with ANC;
                switch to that DC; wait to receive DATA from S; send  ACK;}
          Else If (receiving CSC){continue;}}}
  If (packet is CTS){ // as a sender
    While (switch to next DC in FAIDCL){
          monitor this DC for T;
          If (this DC is busy){
                If (node occupying this DC is not a neighbor of R){
                send CSC on this DC to inform R to switch again;}}
          Else { send DII on this DC to R;
                If (receiving DII) {
                     switch to CC; inform neighbors  occupied DC with ANC;
                     switch to that DC; send DATAs to R;}
                Else if (receiving CSC) {continue;}}}}
  If (packet is ANC){ update CUI; } };// as a neighbor
  If (packet is ACK){ send next DATA; } };// as a sender
```

D. The Illustration of M&M

An illustration of M&M is shown in Fig.2, which involves one CC and three DCs. Three node-pairs, i.e., *AB*, *CD*, and *EF*, are communicating on DC_2, DC_2 and DC_1, respectively. *G* is a neighbor of *S*, and *H* is a neighbor of *R*. Both *G* and *H* are sleeping at the beginning, and *G* wakes up later. Both *S* and *R* overheard the channel announcements of *AB* and *CD*, but missed that of *EF* due to communications on the DC. As *S* has packets for *R*, three phases must be accomplished as follows.

(1) Handshake Phase $[t_0, t_1]$: Based on its CUI, *S* computes *AIDCL* recording that DC_1 and DC_3 are idle, and then *S* sends a *RTS* with *AIDCL* to *R*. When *R* receives this *RTS*, *R* computes its own *AIDCL*, and then computes *FAIDCL* via *AIDCL*s of *R* and *S*, and finally sends a *CTS* with *FAIDCL* back to *S*.

(2) Channel Announcement Phase $[t_1, t_2]$: Assume DC_1 is the first DC in *FAIDCL*, and then both *S* and *R* switch to DC_1 and listen for time *T* and 2*T* where *T* is set according to the maximum data packet size. Because DC_1 is occupied by *EF*, both *S* and *R* could receive a packet from *E*, which means that DC_1 is busy. Therefore, both *S* and *R* continue to switch to DC_3 without sending *CSC* since they both aware of that *E* is their common neighbors. After monitoring DC_3, *S* and *R* exchange *DII* to make sure that DC_3 is idle for both of them due to the

multi-hop hidden terminal problem. Then, S and R switch to the CC, and sequentially send the same ANC about this channel selection, which helps their idle neighbors on the CC (e.g., G) to update their CUIs.

(3) Data Communication Phase$[t_2, t_3]$: S and R switch back to DC_3 and communicate with each other by $DATAs/ACKs$ exchanging. When these exchanging are over, S and R switch back to the CC again and update their CUIs via overhearing the ANCs sent by their communicating neighbors on the CC.

IV. Performance Evaluation

In this section, both simulation and real testbed experiments are conducted to examine the performance of M&M in subsection *A* and subsection *B*, respectively.

A. Simulation Experiments

A homemade simulator is involved for performance comparisons. The simulation is set up as follows. 289 nodes, whose radio communication ranges are set to 40m, are uniformly deployed in a square area of size 200m × 200m with a node density of 38 (i.e., a node that is not at the edge of the network has 37 neighbors). The traffic model that all packets are delivered from many sources to many destinations is used in the simulation where the payload size is set to 32 Bytes and the channel bandwidth is set to 250 Kbps.

To investigate the values of multiple channel reservation, M&M is compared with four mcMACs. (1) CSMA\CA that is a classic single channel MAC protocol; (2) MMSN [4] that is a typical synchronous mcMAC with a static channel selection; (3) PMC [6] that is an asynchronous mcMAC with a dynamic channel selection; (4) CAM-MAC [7] that is a synchronous mcMAC with DISH. Further, three versions of M&M are involved in comparisons. The first one with the duty cycle of 50% utilizes single-channel reservation, called M&M-SCR, which is used to justify values of multiple channel reservation. Moreover, other two versions of M&Ms, i.e., M&M-10% and M&M-50%, use the duty cycle of 10% and 50%, respectively.

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.

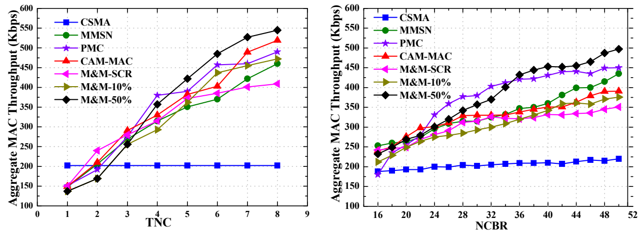
1) *Evaluation on throughput*: The throughput is computed as the total amount of all useful data packets successful delivered via the MAC layer of the network per unit time. Intuitively, M&M would have small throughput than other protocols due to its duty cycle scheme, but M&M is expected to increase throughput by efficiently solving CCP.

When the total number of channels is increased, the throughput changes are shown in Fig.3 (a). Compared with others, M&M-10% and M&M-50% lower throughput when the total number of channels is small than 4. Beside the duty cycling, this is also due to that under multiple channel reservation of M&M all node-pairs have to switch back to the CC first to send an ANC, and then communicate on the DC. This scheme will pay a considerable cost if the total number of channels is small. When more channels are available, M&M, CAM-MAC and PMC allow more nodes to communicate on different DCs simultaneously. This is because they employ dynamic channel selections, and thus outperform CSMA\CA and MMSN. However, when the total number of channels becomes larger, M&M-50% performs a little better than CAM-MAC and PMC. This is because CAM-MAC suffers from collisions of cooperative packets and PMC suffers from CCP, whereas M&M-50% avoids using cooperative packets and tackles CCP by multiple channel reservation, so it achieves higher throughput. Moreover, M&M-10% and M&M-50% outperform M&M-SCR due to their multiple channel reservation.

The throughput is explored when different network loads are used in Fig.3 (b). It is observed that the throughputs of all protocols rise with the number of CBR streams. This is because if more node-pairs are involved in communications, more parallel transmissions will occur on the DCs. Under light loads, M&M-50% is suboptimal to other protocols. Nevertheless, the results show that under heavy loads, M&M-50% performs progressively better than other protocols, which shows that M&M significantly benefits from the multiple channel reservation when the degree of CCP increases with the network loads, even though it is still duty cycling. Again, M&M-50% and M&M-10% outweigh M&M-SCR when loads are heavy.

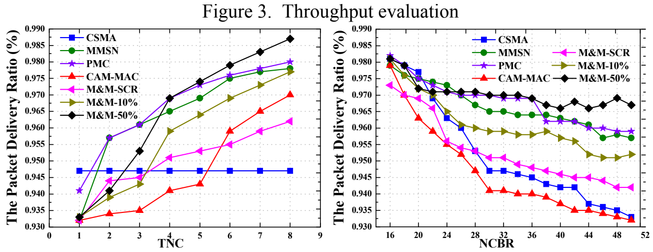
2) *Evaluation on packet delivery ratio*: Packet delivery ratio is computed as the ratio of the total number of packets that MAC layer successful delivered, and the total number of packets that the upper-layer requests MAC layer to deliver. By avoiding that more than one node-pair in neighborhood communicate on the same DC and by sending packets before they are droped due to exceeding their lifetime, M&M is expected to increase packet delivery ratio compared with others.

When total number of channels is increasing, packet delivery ratio changes are observed in Fig.4 (a). The results show that all packet delivery ratios increase with the rise of the total number of channels. When total number of channels is smaller than 4, MMSN and PMC achieve better performances than CAM-MAC and M&Ms. One possible reason is that schemes of CAM-MAC and M&Ms for tackling CCP undermine packet delivery ratio. However, when the total number of channels is larger than 5, M&M-50% outperforms others, but M&M-10% and M&M-SCR still perform worse than MMSN, and PMC. This is primarily because M&M does not involved retransmission scheme. In addition, M&M-10% has a low duty cycle and senders under M&M-SCR drop some packets due to that the single channel reservation cannot reserve a DC in time.



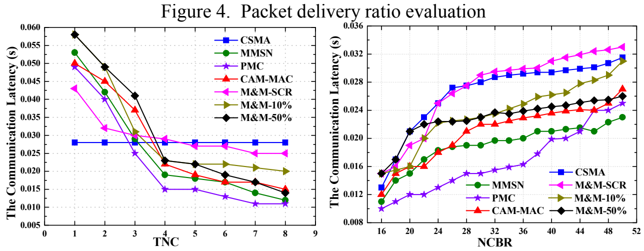
(a)Throughput vs. Total Number of Channels (b) Throughput vs. Loads

Figure 3. Throughput evaluation



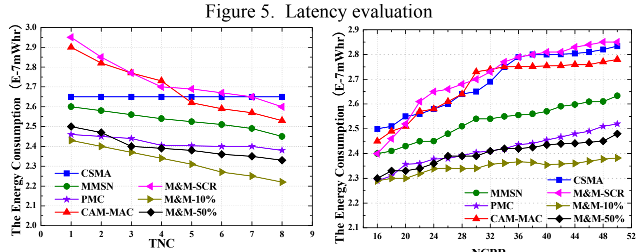
(a) PDR vs. Total Number of Channels (b) PDR vs. Loads

Figure 4. Packet delivery ratio evaluation



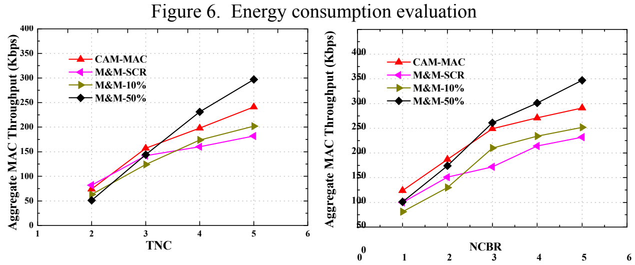
(a) Latency vs. Total Number of Channels (b) Latency vs. Loads

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

The packet delivery ratio is measured via varying the network loads in Fig.4 (b). It is observed that all packet delivery ratios generally drop when the loads are heavier except that of M&M-50%, which maintains stable around 96%-97%. This is because under multiple channel reservation, node-pairs more likely find an idle DC for communication timely before the packets are dropped by the sender due to exceeding lifetime of these packets. Moreover, even M&M-10% outperforms M&M-SCR, which verifies values of multiple channel reservation. MMSN and PMC outperform M&M-10% and MSN-SCF, which is still due to the low duty cycle and flaws of single channel reservation. Note that CAM-MAC has a lower packet delivery ratio than all protocols, which is because the collisions on the CC between the reservation packets and cooperative packets become more serious when loads are heavier.

3) *Evaluation on latency*: The communication latency reflects time delay that a data packet from the upper-layer waits for a channel reservation until this packet is sent. Intuitively, M&Ms will bring longer latency than others due to its duty cycling scheme and the multiple switching among the DCs, but the results show that the difference between these protocols is negligible when CCP becomes more serious.

When the total number of channels is increasing, the latency changes are observed in Fig.5 (a). The results show that compared with others, M&M-10% and M&M-50% have 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 CCP, which is effectively handled by multiple channel reservation in M&M. M&M-SCR 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, CCP is less critical; whereas when the number is becoming larger, CCP greatly undermines the transmission under single channel reservation.

The latency is explored in Fig.5 (b), when different the network loads are used. It is observed that when the network loads are light, M&M-50% has a larger latency than other protocols. However, when CCP becomes more severe as the loads are heavier, the gap between M&M-50% and other protocols on latency becomes narrower. This is mainly because M&M effectively addresses CCP. Moreover, M&M-10% involves larger latency than M&M-50% as expected, and M&M-SCR also has a larger latency due to that single channel reservation results in the multiple handshakes on the CC. MMSN and CAM-MAC achieve greatly lower latency than M&Ms when the network loads is small. This is also due to that when the loads are small CCP 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 M&M-50% 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 protocols is computed as the energy consumed to successfully deliver a useful data byte. Under M&M, the tranmission node-pair are expected to achieve energy efficiency shown by low energy consumption, via avoiding the energy wastage for time synchronization and the retransmission caused by CCP.

As the total number of channels increasingly increases, the energy consumption changes are observed in Fig.6 (a). The results show that energy consumptions of all protocols decrease with the rise of the total number of channels, but M&M-10% outperforms others all the time due to its low duty cycle, and M&M-50% outperforms others at most of time due to its effective multiple channel reservation to handle CCP. All these results indicate that M&M can conserve more energy to prolong the lifetime of WSNs by its lower duty cycle and effective solution to CCP. In addition, the energy conservation that M&M-10% and M&M-50% achieve is also because of avoiding time synchronization of MMSN and continuously channel switching of PMC. Note that M&M-SCR consumes more energy than others due to that its single channel reservation needs more energy to handle the collision caused by CCP. In addition, CAM-MAC consumes higher energy than others due to its collisions of cooperative packets, which undermines many communications when CCP is more serious. PMC achieves better energy efficiency than MMSN all the time, which shows that the continuously channel switching consumes less energy than time synchronization used by MMSN. Last but not least, it is worth noting that when the total number of channels is becoming larger, the gap between M&M-10% and M&M-50% on energy consumption is becoming larger, which could indicate that M&M with low duty cycle is capable of achieving higher energy efficiency under the network with more DCs.

The energy consumption is measured by varying the network loads. In Fig.6 (b), all energy consumptions increase when the loads rise. The energy consumption of M&M-10% becomes generally stable when the number of CBR streams is larger than 38, which means that the M&M with low duty cycle is more suitable with the network with higher loads. In addition, M&M-10% and M&M-50% maintain lower energy consumption than others when the number of CBR streams is larger than 24. This is because other protocols suffer from certain problems. Note that MMSN consumes much energy to maintain time synchronization, which becomes more tricky when the network loads are heavy. PMC has many collisions on the current channel as the network loads are becoming heavier. In addition, under PMC the sender is supposed to switch lots of channels to communicate with the receiver that has different loads with the sender. CAM-MAC seriously suffers from collisions between cooperative packets and reservation packets on the CC when more node-pairs communicate simultaneously, which also indicates that fewer neighbor nodes are left to cooperate with communicating node-pairs. M&M-SCR is still affected by multiple handshakes on the CC caused by CCP.

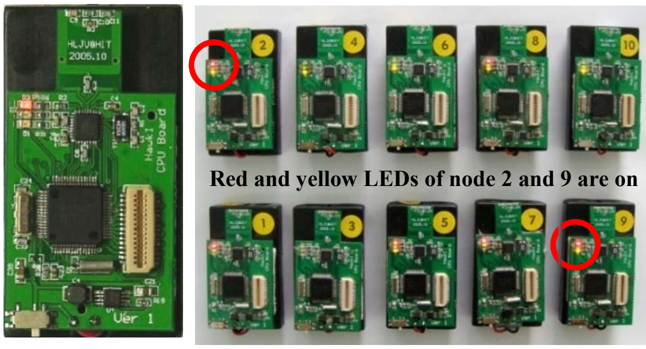
B. Testbed Experiments

In this subsection, several testbed experiments are conducted to evaluate the performance of M&M, which is implemented in the μC/OS [23] on Hawk. Hawk is a sensor node platform developed by Heilongjiang University, where node is equipped with nRF905 radio and MSP430 processor. A picture of hawk node is shown in Fig.8 (a). For visualization purposes, three LEDs are used (i.e., red, green, and yellow) on each node to indicate specific events. For example, the red LED being on indicates the node is communicating on a DC. Meanwhile the green and the yellow LED jointly indicate the specific number of DC (a maximum of $2^2=4$ DCs can be represented), e.g., in Fig.8 (b) the red and yellow LEDs of node 2 and 9 are on, which indicates they are communicating on the DC_3. Whereas, the red LED being off and the yellow and green LEDs being on jointly indicate the node is overhearing on the CC. All LEDs being off indicates the node is sleeping.

The testbed consists of 10 hawk nodes deployed within one hop as in Fig.8 (b) where all nodes are within the communication range of each other, which was also used by Lou *et al*. [7]. The multi-hop experiments are left for future work. The size of packets is set to 32 Byte, and data transmission rate is set to 100 Kbps. All nodes randomly choose a neighbor to enable a communication for throughput comparisons.

The experiment repeats for 10 times, and when an experiment is over, all nodes send their total amount of data received during the experiment to a sink node one by one, 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 M&M-10%, M&M-50%, M&M-SCR and CAM-MAC are implemented for comparisons.

The throughput is explored as the different total number of channel is used. The number of CBR streams is set to 5. From Fig.7 (a), it is observed that CAM-MAC has higher throughput than M&M-50% when the total number of channels is less than 4. This is primarily because CAM-MAC does not have to enable duty cycling or switch among DCs, which undermine the throughput of M&M-50% when CCP is less serious. Nevertheless, M&M-50% achieves better throughput when the total number of channel is larger than or equal to 4. A possible explanation of this improvement is that when more DCs are available, CCP becomes more serious, and M&M tackles CCP with less cost than CAM-MAC. These results are generally consistent with the simulation comparison results shown in Fig.4 (a). In addition, M&M-50% has similar throughput with M&M-SCR and M&M-10% when the total number of channels is small, whereas M&M-50% outperforms them as the total number of channels is larger than 3. It is worth noting that M&M-50% outperforming M&M-10% is due to its higher duty cycle than M&M-10%, while results that M&M-50% outperforms M&M-SCR further justify values of multiple channel reservation adopted by M&M.



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

Figure 8. Testbed experiments

When the number of channels is set to 5 and the network loads are varying, the throughput is observed in Fig.7 (b). It shows that all three M&M based protocols have lower throughput than CAM-MAC as the network loads are small. This is mainly because when fewer nodes are involved in communication, the cooperative scheme of CAM-MAC works better to tackle CCP than multiple channel reservation of M&M. Nevertheless, when the network loads are becoming heavier, fewer nodes are left as cooperative neighbors to send cooperative packets, which are employed by CAM-MAC to prevent CCP. Therefore, M&M-50% outperforms CAM-MAC when the number of CBR Stream is equal to or larger than 3. This is also due to that when the network loads are heavier M&M avoids the collision between cooperative packets and reservation packets on the CC under the cooperation scheme in CAM-MAC. Finally, note that M&M-50% works better than M&M-SCR and M&M-10%. More importantly, the gap on the throughput between M&M-50% and others becomes larger when the network loads are heavier, which shows that multiple channel reservation and higher duty cycle actually improve the throughput of M&M-50% under the network with higher loads.

V. Conclusion

Channel conflict is a major source of energy wastage in multi-channel WSNs. To address this problem, a duty cycle based MAC protocol, called M&M, with multiple channel reservation is presented in this paper. Being fully distributed with no requirements of time synchronization or multi-radio scheme, M&M is suitable to be implemented in large-scale WSNs. Moreover, extensive simulation experiments are conducted to examine the performance of M&M. The results show that with multiple channel reservation, M&M can solve channel conflict problem with a lower cost, and still enable duty cycling at same time. Therefore, M&M achieves a significant improvement of the energy efficiency with increasing benefit when the total number of channels and loads increase. To investigate M&M's real performance, M&M is also implemented in a real sensor platform in this paper. The testbed experiment results show that multiple channel reservation actually enables M&M to achieve better throughput when the number of channels is larger and the network loads are heavier.

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