This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

RCS: a Random Channel Selection with Probabilistic Backoff for Multi-Channel MAC Protocols in WSNs

Jinbao Li[1,2], Desheng Zhang[1,2], Shouling Ji[3], and Longjiang Guo[1,2]
[1] School of Computer Science and Technology, Heilongjiang University, Harbin, Heilongjiang, China, 150080
[2] Key Laboratory of Database and Parallel Computing of Heilongjiang Province, Harbin, Heilongjiang, China, 150080
[3] Department of Computer Science, Georgia State University, Atlanta, GA, USA, 30303
jbli@hlju.edu.cn, zhang.de.sheng@qq.com, sji@cs.gsu.edu, lguo@gsu.edu

Abstract—**This paper proposes a new Random Channel Selection scheme with probabilistic backoff, called RCS, for a class of multi-channel MAC protocols in heavy loads WSNs to tackle the channel conflict problem. By adopting RCS, a node can reduce the probability of selecting a busy channel for data communication. Therefore, RCS can avoid data packet collision, and thus conserve more energy to extend the lifetime of WSNs. More importantly, RCS is fully distributed with no requirements of time synchronization or multi-radio, so it is practical to realize RCS in resource-constrained sensor nodes. In theoretical analysis, the probability of a channel conflict creation and the average number of misunderstood channels are obtained, which can guide the configurations of RCS. More importantly, RCS is evaluated in both simulation and testbed experiments, and results indicate that as the number of channels and loads increase, RCS significantly improves throughput and energy efficiency as well.**

I. INTRODUCTION

To remedy the drawback of single channel MAC protocols, the multi-channel MAC protocols (**mcMAC**) [1] [2] [3] have been proposed to improve the performance of WSNs via parallel transmissions, which are supported by the current sensor nodes, such as MICA2 with more than 50 channels.

A mcMAC consists of *channel selection* and *media access*. Channel selection decides how to select idle channels for nodes in order to optimize the performance of WSNs; whereas media access decides when and how nodes access the channels that have been selected for them. This paper focuses on channel selection schemes, which can be classified as *static* and *dynamic*. In static schemes such as [1], every node in the network chooses a *dedicated* channel to receive data, and switches to other channels to send data. Static schemes have to guarantee to select different channels for nodes within two-hop neighborhood to avoid collision. Thus, the number of channels required in static schemes is *at least* as large as two-hop node number [3]. To tackle this issue, dynamic schemes such as [2] [3] [4] assign channels to node-pairs *on demand*. Thus, the number of channels required in dynamic schemes is *at most* half of the two-hop node number plus one [3], which is the number of Control Channel (**CC**) for Data Channel (**DC**) reservations.

Dynamic channel selection schemes can address problems in static schemes, but they sometimes fail to provide satisfactory performance due to the Channel Conflict Problem (**CCP**). As shown in [3] [5], CCP is one of the most significant sources of energy wastage in multi-channel scenario. CCP results from that the usage information of a channel may not be timely learned by all senders. Therefore, when a sender selects an Assumed Idle DC (**AIDC**) for data communication, this channel may be already being used by other nodes.

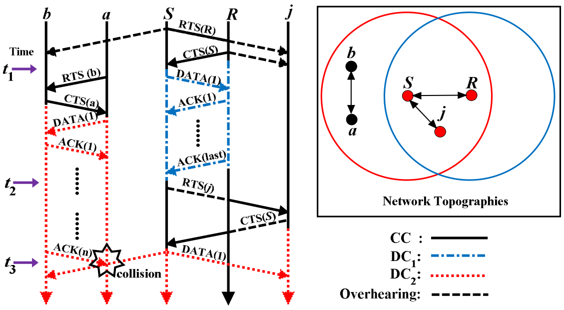


Figure 1. The illustration of channel confliction

An illustration of CCP is given in Fig.1, which involves one CC and two idle DCs. When node S has data for node R, S randomly selects an idle DC such as DC$_1$ and puts reservation information (e.g., who will occupy which channel for how long) into a RTS sending to R on the CC. Then, to confirm this RTS, R sends a CTS back to S. Next, they switch their channels to DC$_1$ around time t_1. All the neighbor nodes of S and R (e.g., a, b and j) update their Channel Usage Information (**CUI**) by overhearing on the CC. During $(t_1,\ t_2)$, a has data for b. a randomly selects an idle DC such as DC$_2$ and switches to DC$_2$ with b after a reservation. Because S and R are on DC$_1$ during $(t_1,\ t_2)$, S and R both still assume DC$_2$ is idle. When S finishes sending data to R, S has data for j. If S also selects DC$_2$ that a and b are still occupying, then a CCP is created, which can cause the packet collision in a or b around t_3.

Aiming at solving CCP, a Random Channel Selection scheme, called RCS, is proposed in this paper with probabilistic backoff for a class of multi-channel MAC protocols under heavy loads. The main idea of RCS is to make a trade-off between the times of CCP creations and the latency. We try to lower the probability of a CCP creation via increasing latency, based on two reasons below. **(1)** CCP can result in data packet collision that is one of the main sources of energy wastage in WSNs. **(2)** Energy efficiency is the primary design goal for MAC in WSNs instead of traditional goals such as latency.

This paper hopes to contribute in the following ways: **(1)** makes the first attempt to apply the idea of random channel selection with probabilistic backoff to tackle CCP in WSNs; **(2)** proposes a robust and scalable channel selection scheme, called RCS, which is fully distributed with no requirements of time synchronization or multi-radio; **(3)** analyzes the performance of RCS and obtains the probability of a CCP creation and the average number of misunderstood channels via probability theory; and **(4)** conducts both extensive simulation and testbed experiments to evaluate the performance of RCS by comparing RCS with other schemes without probabilistic backoff.

978-1-4244-5638-3/10/$26.00 ©2010 IEEE

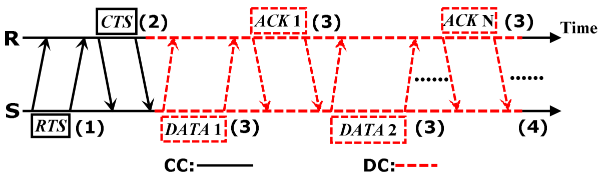


Figure 2. Communication scheme

II. RANDOM CHANNEL SELECTION

Two assumptions are made as follows: **(1)** wireless bandwidth is divided into one CC for control information exchanging and K DCs for data communication, and every channel is orthogonal to the others; **(2)** all nodes are assumed to be equipped with a same switchable half-duplex radio.

A. Communication Scheme of mcMACs

When nodes in mcMACs are idle, they monitor the CC. After they actually overheard a reservation packet, they update their CUI, which is used for channel selection when they have messages to send. As nodes actually have messages to send, the following four steps must be accomplished as in Fig.2. **(1)** When the sender S has a message to send to its receiver R, S selects an AIDC based on its channel selection. Then, under CSMA/CA scheme, S sends a RTS with channel reservation information to R on the CC. **(2)** After R receives this RTS, R send a CTS to confirm this reservation on the CC. Note that the CTS holds the same information as the RTS. Next, R switches its channel to the DC that S has selected before and waits for $DATA$s. **(3)** After S receives this CTS, S also switches its current channel to the same DC and employs CSMA/CA scheme to send a series of $DATA$s belonging to a message to R; after R receives each $DATA$, R sends an ACK to S to confirm it. Finally, when R sends out its last ACK, it switches its channel back to the CC to overhear again. **(4)** After S receives the last ACK, S also switches back to the CC to overhear again.

B. Design of RCS

RCS works in the first step of the above mcMACs. When S has a message to send, S solves the probability (denoted by p) that the AIDC S has selected in this time is being used by other nodes. After solving p, instead of uniformly selecting an AIDC and initiating a channel reservation handshake with R immediately, S does these two actions together with the probability of $1-p$, or backs off at random with p and tries to do these two actions after a period of time (addressed in Section IV.***A***). The objective of the backoff with p is to reduce the probability of a CCP creation during this channel selection, and then to reduce the probability of packet collision on DCs, and finally to conserve energy to extend the lifetime of WSNs. Note that the receiver-decided channel selection is not used in RCS, since in mcMACs a sender *also* receives ACKs from its receiver. In addition, a sender can send its whole CUI to its receiver, and let its receiver selects an AIDC for both of them. However, this scheme not only induces *overhead* due to the size of whole CUI, but the AIDC the receiver selected can be *busy* due to CCP.

During the lifetime of nodes, p is constantly varying according to underlying network parameters estimated by nodes in real-time. The RCS performance is highly dependent on the accurateness of p, which characterizes the intensity of channel conflict. The detailed analysis of p is discussed as follows.

III. THEORETICAL ANALYSIS

An analysis of RCS performance is made by solving p in this section. The symbols used in the analysis are listed in Table I. Let v be any node in the network. p is solved by introducing the average total number of MCs, denoted by k'. Let

$$p = k' / (K-k)\,. \tag{1}$$

Therefore, p represents the probability of v selecting a busy DC from all AIDCs according to current CUI, where K and k are known. k' is solved by introducing p_{mc}, and p_{mc} is solved by introducing $\Pr[MCR_i]$, and finally $\Pr[MCR_i]$ is solved.

A. Solving k'

Let $\Pr[MC(m)]$ be the probability that v has m MCs. Then,

$$k' = \textstyle\sum_{m=0}^{K-k} m \cdot \Pr[MC(m)]. \tag{2}$$

Let p_{mc} be the probability of a MC creation. Assuming the creation of a MC is independent of each other, then

$$\Pr[MC(m)] \approx C_{K-k}^{m} \cdot {p_{mc}}^{m} \cdot (1-p_{mc})^{K-k-m}. \tag{3}$$

Because m, K and k are known, we can solve (1) via (2), then solve (2) via (3), and then solve (3) via (4) in subsection ***B***.

B. Solving p_{mc}

By the Total Probability Theorem (**TPT**),

$$p_{mc} = \Pr[EMC|\overline{MCR}] \cdot \Pr[\overline{MCR}] + \Pr[EMC|MCR] \cdot \Pr[MCR]. \tag{4}$$

We solve (4) by (5) and (6) below, and (11) in subsection ***C***.

The only reason why an EMC happens is that v misses the channel reservation packet from a neighbor, therefore

$$\Pr[EMC|\overline{MCR}] = 0. \tag{5}$$

Let i be an arbitrary neighbor of v, so $\Pr[MCR]$ is equal to $\Pr[MCR_i]$. Then let j be an arbitrary neighbor of i, so

$$\Pr[EMC|MCR] = \Pr[EMC|MCR_i|j \in N_{vi}] \cdot \Pr[j \in N_{vi}] + \Pr\left[EMC|MCR_i\middle|j \in N_{v\setminus i}\right] \cdot \Pr\left[j \in N_{v\setminus i}\right]. \tag{6}$$

1) $\Pr[j \in N_{vi}]$and$\Pr\left[j \in N_{v\setminus i}\right]$: Assume that i sends data to its neighbors uniformly and all nodes are placed in an area with a two-dimensional Poisson point process, so by [5],

$$\Pr[j \in N_{vi}] \approx 1.84 / 3.14, \quad \Pr\left[j \in N_{v\setminus i}\right] \approx 1.30 / 3.14. \tag{7}$$

2) $\Pr\left[EMC|MCR_i\middle|j \in N_{v\setminus i}\right]$: Since $j \in N_{v\setminus i}$, if v misses the reservation packet of i, an EMC will definitely happen, thus

$$\Pr\left[EMC|MCR_i\middle|j \in N_{v\setminus i}\right] = 1. \tag{8}$$

3) $\Pr[EMC|MCR_i|j \in N_{vi}]$: If $j \in N_{vi}$ and MCR_i happens, an EMC happens if and only if MCR_j happens, therefore

$$\Pr[EMC|MCR_i|j \in N_{vi}] = \Pr\left[MCR_j|MCR_i|j \in N_{vi}\right]. \tag{9}$$

$\Pr[MCR_j|MCR_i|j \in N_{vi}]$ is equal to the probability that v misses both the channel reservation packets of i and j. Therefore, it can be derived from [5] that

$$\Pr\left[MCR_j|MCR_i|j \in N_{vi}\right] = \frac{T_{DC}-T_{CR}}{T_{DC}}. \tag{10}$$

TABLE I. SYMBOL TABLE

	Symbols	Meanings
Probabilities	p_{cc}	a node is on the CC at an arbitrary time
	p_{mc}	a MC is created in long run
	p_{rcv}	a node switches to a DC as a ReCeiVer
Events	EMC	Event that a MC is created
	$MCR_{(i)}$	v Misses a Channel Reservation from a neighbor (e.g., i)
	IIS	node i Is a Sender
	$OCC_v(t)$	node v is On the CC at time t
	$NSC_v(T_{iR})$	v is Not Sending on the CC during T_{iR}
	$NIC_u(T_{iR})$	u does Not Interfere with nodes on the CC during T_{iR}
	$BTC(T_{iR})$	u switches Back To the CC during T_{iR}
Others	MC	an AIDC that is actually busy
	λ	average data packet arrival rate at each node
	$K; k$	total number of DCs; number of Assumed busy DCs
	AVG	average number of packets in a message
	T_{CR}	duration of a Channel Reservation handshake
	T_{DC}	duration of message communication on a DC
	$N_i; N_{vi}; N_{v\backslash i}$	neighbor set of i; $N_{vi} = N_v \cap N_i$; $N_{v\backslash i} = N_v \backslash N_i \backslash \{i\}$
	N	a non-edge node has 3.14N neighbors (density)

C. Solving $\boldsymbol{Pr[MCR_i]}$

Because $\Pr[MCR_i] = 1 - \Pr[\overline{MCR_i}]$, by TPT,

$$\Pr[\overline{MCR_i}] = \Pr[\overline{MCR_i}|IIS] \cdot \Pr[IIS] + \Pr[\overline{MCR_i}|\overline{IIS}] \cdot \Pr[\overline{IIS}]. \quad (11)$$

We solve (11) by (12) in subsection ***1)***, (13) and (14) in ***2)***.

1) $\boldsymbol{Pr[IIS]}$ ***and*** $\boldsymbol{Pr[\overline{IIS}]}$: Since i is an arbitrary neighbor of v, in the long run,

$$\Pr[IIS] \approx \Pr[\overline{IIS}] \approx 1\ /\ 2. \quad (12)$$

2) $\boldsymbol{Pr[\overline{MCR_i}|IIS]}$ ***and*** $\boldsymbol{Pr[\overline{MCR_i}|\overline{IIS}]}$: If i is a sender, $\overline{MCR_i}$ happens if and only if conditions below are met. **(1)** v is on the CC at the time (denoted as $t_{i,R}$) that i starts to send a RTS; **(2)** v is not sending in the interval that i is sending the RTS (denoted as T_{iR}, i.e.,$(t_{i,R}, t_{i,R} + T_{CR})$); **(3)** all neighbors of v except i do not interfere with v on the CC in the interval T_{iR}. Therefore,

$$\Pr[\overline{MCR}_i|IIS] = \Pr\,[OCC_v(t_{i,R}), NSC_v\,(T_{iR}), \cap_{u \in N_v \backslash \{i\}} NIC_u(T_{iR})]. \quad (13)$$

Similarly, if i is a receiver, then

$$\Pr[\overline{MCR}_i|\overline{IIS}] = \Pr\,[OCC_v(t_{i,C}), NSC_v\,(T_{iC}), \cap_{u \in N_v \backslash \{i\}} NIC_u(T_{iC})]. \quad (14)$$

Due to space limitations and the similarity between (13) and (14), we just show that how to solve (13) via (15) as follows.

If v is on the CC at $t_{i,R}$ (i.e., an $OCC_v(t_{i,R})$ happens), $NSC_v\,(T_{iR})$ will always happen since most MAC protocols do not allow v to send as i is sending a RTS. If assuming that the $OCC_v(t_{i,R})$ and the $NIC_u(T_{iR})$ are independent of each other, so are all the $NIC_u(T_{iR})$s, then, approximately,

$$\Pr[\overline{MCR}_i|IIS] \approx \Pr[OCC_v(t_{i,R})] \cdot \Pr[NIC_u(T_{iR})]^{|N_v \backslash \{i\}|}. \quad (15)$$

We can solve (15) via (16) in subsection ***a)*** and (18) in ***b)***.

a) $\boldsymbol{Pr[OCC_v(t_{i,R})]}$: For v, $t_{i,R}$ is an arbitrary moment, so

$$\Pr[\,OCC_v(t_{i,R})] = p_{cc}. \quad (16)$$

Let T_0 be a sufficiently long time. During T_0, the total number of arrival messages at each node equals $\lambda T_0/AVG$, so the total time, that a node sends all these messages on DCs, equals $\lambda T_0 T_{DC}/AVG$. While, approximately, the total time, that a node receives all these messages, is $p_{rcv}(1 - p_{cc})T_0$. In the long run, the total time that a node sends messages equals the total time that a node receives messages, when the network is stable (after a sufficiently long time). If assuming $p_{rcv} \approx 1/2$,

$$p_{cc} \approx 1 - 2\lambda T_{DC}/AVG. \quad (17)$$

b) $\boldsymbol{Pr[NIC_u(T_{iR})]}$: If $u \in N_{vi}$, $NIC_u(T_{iR})$ always happens since u is not allowed to send on the CC when its neighbor i is sending RTS, no matter u is on the CC or DC at $t_{i,R}$, so by (7),

$$\Pr[\bigcap_{u \in N_v \backslash \{i\}} NIC_u(T_{iR})] = \Pr[NIC_u(T_{iR})]^{|N_{v\backslash i}|} = \Pr[NIC_u(T_{iR})]^{1.30N}, \quad (18)$$

where $1.30N$ is the number of v's neighbors $\in N_{v\backslash i}$.

$$\Pr[NIC_u(T_{iR})] = \Pr[NIC_u(T_{iR})|u \in N_{vi}] \cdot \Pr[u \in N_{vi}] + \Pr[NIC_u(T_{iR})|u \in N_{v\backslash i}] \cdot \Pr[u \in N_{v\backslash i}]. \quad (19)$$

We have solved $\Pr[u \in N_{vi}]$ and $\Pr[u \in N_{v\backslash i}]$ in (7), so we can solve (19) by (20) and (21) in subsection ***c)***.

c) $\boldsymbol{Pr[NIC_u(T_{iR})|u \in N_{vi}]}$ ***and*** $\boldsymbol{Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}]}$: If $u \in N_{vi}$, by the same reason in (18),

$$\Pr[NIC_u(T_{iR})|u \in N_{vi}] = 1. \quad (20)$$

$$\Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}] = \Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}|OCC_u(t_{i,R})] \cdot \Pr[OCC_u(t_{i,R})] + \Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}|\overline{OCC_u(t_{i,R})}] \cdot \Pr\left[\overline{OCC_u(t_{i,R})}\right]. \quad (21)$$

We have solved $\Pr[OCC_u(t_{i,R})]$ in (16), therefore we can solve (21) via (22) and (23) in subsection ***d)***.

d) $\boldsymbol{Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}]}$: Assuming Possion arrival, if $u \in N_{v\backslash i}$, u does not interfere with v overhearing RTS of i if and only if u keeps silent during $(t_{i,R} - T_{CR}, t_{i,R} + T_{CR})$, so

$$\Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}|OCC_u(t_{i,R})] = \mathrm{e}^{-2\lambda T_{CR}}. \quad (22)$$

If $u \in N_{v\backslash i}$, by the TPT,

$$\Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}|\overline{OCC_u(t_{i,R})}] = \Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}|\overline{OCC_u(t_{i,R})}|BTC(T_{iR})] \cdot \Pr[BTC(T_{iR})] + \Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}|\overline{OCC_u(t_{i,R})}|\overline{BTC(T_{iR})}] \cdot \Pr[\overline{BTC(T_{iR})}] \quad (23)$$

We can solve (23) via (24), (25) and (26) in subsection ***e)***.

e) $\boldsymbol{Pr\,[NIC_u(T_{iR})|u \in N_{v\backslash i}|\overline{OCC_u(t_{i,R})}]}$:The time that u switches back to the CC is uniformly distributed in the interval T_{iR}, since when u switches to the DC is unknown. Therefore,

$$\Pr[BTC(T_{iR})] = \frac{|T_{iR}|}{T_{DC}} = \frac{T_{CR}}{T_{DC}}. \quad (24)$$

If $u \in N_{v\backslash i}$, since u does not switch its current channel back to the CC during $(t_{i,R}, t_{i,R} + T_{DC})$,

$$\Pr\,[NIC_u(T_{iR})|\overline{OCC_u(t_{i,R})}|\overline{BTC(T_{iR})}] = 1. \quad (25)$$

Let Δt be the duration that u is on the CC after u switches back to the CC. Based on the similar reason with (24), Δt is uniformly distributed in $(0, T_{CR})$. Therefore, If $u \in N_{v\backslash i}$, then

$$\Pr\,[NIC_u(T_{iR})|\overline{OCC_u(t_{i,R})}|BTC(T_{iR})] = \frac{1 - e^{-\lambda T_{CR}}}{\lambda T_{CR}}. \quad (26)$$

IV. PERFORMANCE EVALUATION

A. Simulation Experiments

A homemade simulator is used for performance comparisons. 289 nodes, with a radio communication range 40m, are uniformly deployed in a square area of size 200m × 200m with a node density of 38. The traffic model is set to that all messages are delivered from many sources to many destinations. The payload size is set to 32 Bytes, and channel bandwidth is set to 250 Kbps. Moreover, backoff time is set to 20ms.

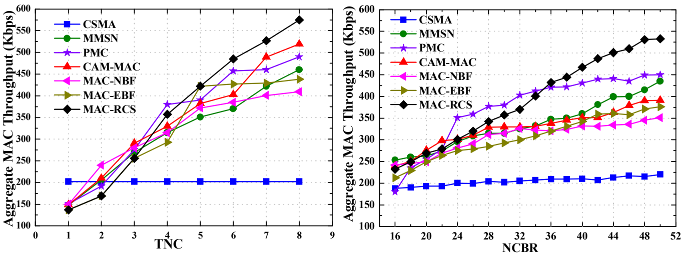
Two groups of simulations are conducted to examine *throughput* and *energy consumption*. Different Total Number of Channels (**TNC**) and loads are considered, which are varied by the change of the number of CBR (**NCBR**, Constant Bit Rate) streams. TNC is set to 4 when NCBR is varying, whereas NCBR is set to 30 when different TNCs are used.

To examine the value of backoff, the mcMAC with RCS (MAC-RCS) is compared to four protocols: CSMA\CA, MMSN [1], PMC [2] and CAM-MAC [3]. Furthermore, two varieties of MAC-RCS are also involved: first variety utilizes Non-Backoff scheme (MAC-NBF); second variety exploits a binary Exponential Backoff scheme (MAC-EBF).

1)Evaluation on throughput: The aggregate throughput is computed as the total amount of all useful data packets successful delivered via MAC layer in the network per unit time. Intuitively, all backoff mcMACs would have smaller throughput than others, but MAC-RCS is expected to increase its throughput by solving CCP, so how MAC-RCS achieves this objective can be shown by this metric.

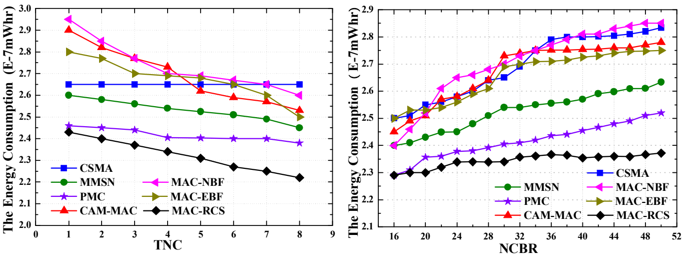
The throughput is explored when different TNCs are used in Fig.3 (a). The results show that the throughputs of different protocols rise when TNC increases. Compared with MMSN, PMC and CAM-MAC, MAC-RCS has a similar or little lower throughput when TNC is small. This is because MAC-RCS uses the two-way handshake and probabilistic backoff scheme, which will pay more cost if TNC is relatively small. However, when TNC becomes larger, MAC-RCS performs better than the others: since CCP becomes more serious, MAC-RCS tackles it with a smaller cost than CAM-MAC, and MMSN or PMS do not address it at all. Moreover, two varieties of MAC-RCS perform better than MAC-RCS as TNC is small, but they maintain stable when TNC becomes more larger, so MAC-RCS outperforms them after all, as TNC is larger than 5.

When NCBR is increasing, the throughput changes are shown in Fig.3 (b). It is observed that the throughputs of all protocols increase with NCBR, because if more node-pairs are involved in communication, more parallel transmissions will occur. However, the results show that under heavy loads, MAC-RCS performs gradually better than other protocols, which illustrates that MAC-RCS significantly benefits from the probabilistic backoff scheme when the probability of packet collision increases with loads. Furthermore, MAC-RCS achieves better throughout than MAC-NBF and MAC-EBF as NCBR is larger than 18 due to that these varieties do not consider CCP in the first place, so they suffer from collision caused by CCP.



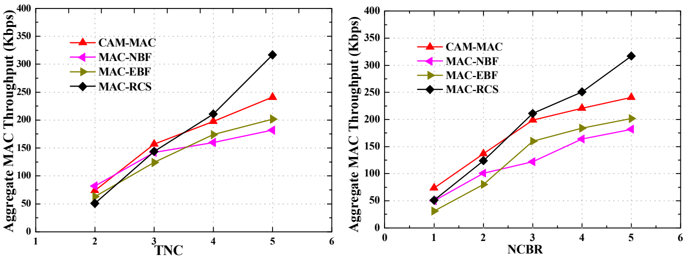
(a) Throughput vs. TNC (b) Throughput vs. NCBR

Figure 3. Throughout evaluation



(a) Energy vs. TNC (b) Energy vs. NCBR

Figure 4. Energy consumption evaluation



(a) Throughput vs. TNC (b) Throughput vs. NCBR

Figure 5. Testbed evaluation on throughput

2)Evaluation on Energy Consumption: For all the protocols, energy consumption is computed as the energy consumed to successfully deliver a useful data byte. MAC-RCS is expected to achieve energy efficiency via probabilistic backoff scheme.

As TNC increases, energy consumption changes are observed in Fig.4 (a). Results show that the energy consumptions of all protocols decrease with the rise of TNC, but MAC-RCS performs better than others all the time, since it conserves energy by avoiding the time synchronization of MMSN and the continuously channel switching of PMC. In addition, MAC-RCS effectively avoids the collision in CAM-MAC as well as MAC-NBF and MAC-EBF, so MAC-RCS avoids the energy consumption caused by retransmissions under them.

The energy consumption is measured by varying loads. In Fig.4 (b), all energy consumptions increase when loads rise. MAC-RCS maintains a relatively low energy consumption since probabilistic backoff scheme reduces the probability of packet collision. Whereas other protocols suffer from certain problems: MMSN consumes more energy to maintain time synchronization; PMC has many collisions on the current channel when loads are heavy; and CAM-MAC, MAC-NBF as well as MAC-EBF still suffer from retransmissions and then consume more energy than other protocols.

978-1-4244-5638-3/10/$26.00 ©2010 IEEE

B. Testbed Experiments

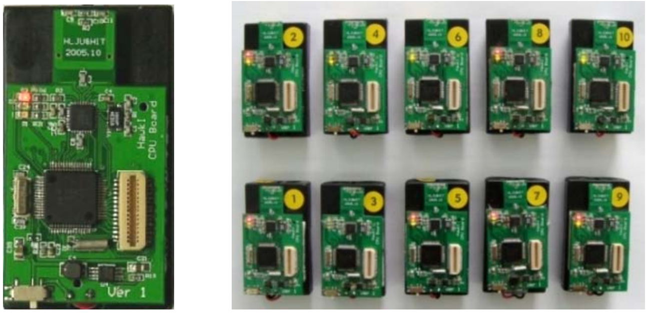
To evaluate the real performance of MAC-RCS, it is evaluated in μC/OS on the hawk node, which is a sensor node platform developed by Heilongjiang University. The hawk node is equipped with nRF905 radio and MSP430 processor, and its picture is shown in Fig.6 (a). For visualization purposes, three LEDs (red, green and yellow) are used on each node to indicate specific events.

Due to the time synchronization of MMSN and the complexity of PMC for parameter computations, only MAC-RCS and CAM-MAC are implemented, compared with two varieties of MAC-RCS, i.e., MAC-NBF with non-backoff scheme and MAC-EBF with a binary exponential backoff scheme. In this testbed experiment, aggregate throughput is examined, which is computed with the same method in the simulation.

The testbed consists of 10 hawk nodes deployed within one hop as in Fig.6 (b). By this setting, all nodes are within the communication range of each other, which was also used by Luo *et al*. [3]. The size of packets is set to 32 Bytes, and the data transmission rate is set to 100 Kbps. All nodes choose a neighbor at random to enable a unicast communication. The experiment repeats 10 times, and when a experiment is over, all nodes sequentially send their total amount of data received during the experiment to the sink, which is a special node connected to a computer, thus the throughput can be obtained.

The throughput is explored as NCBR is set to 5 and the different TNC is used. From Fig.5 (a), it is observed that CAM-MAC has higher throughput than MAC-RCS and its two varieties, when TNC is less than or equal to 3. CAM-MAC does not have to back off, as nodes have packets to send; whereas backoff compromises the throughput of MAC-RCS, when CCP is less serious. However, MAC-RCS achieves better throughput as TNC is larger than or equal to 4. The explanation of this improvement is that when more DCs are available, CCP becomes more serious, and MAC-RCS tackles it with less cost than CAM-MAC. In addition, MAC-RCS has similar or little lower throughput compared with MAC-NBF and MAC-EBF when the total number of channels is small, while it outperforms them, as 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 probabilistic backoff scheme.

When TNC is set to 5 and loads are varying, the throughput is observed in Fig.5 (b). It shows that MAC-RCS and its two varieties have lower throughput than CAM-MAC, as loads are small. This is due to when fewer nodes are communicating, cooperative scheme of CAM-MAC works better in tackle CCP than probabilistic backoff scheme of MAC-RCS. However, when loads are heavy, fewer nodes are left for cooperation, so collision becomes more serious. Therefore, MAC-RCS outperforms CAM-MAC as NCBR is equal to or larger than 3. Note that MAC-RCS performs better than MAC-NBF and MAC-EBF all the time. Once again, these results are generally consistent with the simulation results shown in Fig.3 (b), which shows that the probabilistic backoff scheme actually improves the throughput of MAC-RCS.



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

Figure 6. Testbed experiments

V. CONCLUSION

To handle Channel conflict, this paper proposes a new Random Channel Selection RCS with probabilistic backoff for heavy loads WSNs. By probability theory, the average number of misunderstood channels and the probability of a channel conflict creation are obtained. The simulation results show that with probabilistic backoff, RCS can reduce the probability that a node selects a channel being used by other nodes. Therefore, RCS achieves significant improvements in the throughput and energy efficiency with increasing benefit, when the number of channels and traffic loads increase. More importantly, RCS is implemented in a real testbed, and the experimental results show that the probabilistic backoff scheme actually enables RCS to achieve better throughput.

VI. ACKNOWLEDGMENTS

This work is partly supported by the National Natural Science Foundation of China for Young Scholar (No.60803015), the Key Scientific and Technological Research Project of Heilongjiang Province of China (No. GC09A109), the China Postdoctoral Science Foundation (No.20080430902), the Heilongjiang Postdoctoral Science Foundation (No.LRB08-021), the Science and Technology Key Research of Heilongjiang Educational Committee (No.1154Z1001), the Graduate Innovative Research Project of Heilongjiang Province of China (No.YJSCX2010-019HLJ), the Science and Technology Innovation Research Project of Harbin for Young Scholar (No.2008RFQXG107), the Foundation of Heilongjiang University for Young Scholar and the Innovative Research and Laboratory Project of Heilongjiang University (No.2010208, No.2010046).

REFERENCES

[1] G. Zhou, C. Huang, T. Yan, T. He, A. Stankovic and T. Abdelzaher, “MMSN: Multi-Frequency Media Access Control for Wireless Sensor Networks,” in *Proc*. of Infocom’06. 2006.

[2] H. Le, D. Henriksson, and T. Abdelzaher, “A Practical Multi-Channel Media Access Control Protocol for Wireless Sensor Networks,” in *Proc*. of International Conference on Information Processing in Sensor Networks (IPSN’08). 2008.

[3] T. Luo, M. Motani, and V. Srinivasan, “Cooperative Asynchronous Multichannel MAC: Design, Analysis, and Implementation,” IEEE Transactions on Mobile Computing. Vol 8, No 3, 2009.

[4] J. So and N. Vaidya, “Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using a Single Transceiver,” in *Proc*. of ACM International Symposium on Mobile Ad Hoc Networking and Computing (Mobihoc’04). 2004.

[5] T. Luo, M. Motani, and V. Srinivasan, “Analyzing DISH for Multi-Channel MAC Protocols in Wireless Networks,” in *Proc*. of ACM International Symposium on Mobile Hoc Networking and Computing (Mobihoc’08). 2008.