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A Short Preamble Cognitive MAC Protocol in Cognitive Radio Sensor Networks

Meng Zheng, Chuqing Wang, Manyi Du, Lin Chen, Wei Liang, and Haibin Yu

***Abstract*—Cognitive radio provides a promising solution to reliable and time-efficient wireless sensor networks. However, cognitive capability brings a quite challenging issue to energy-constrained cognitive radio sensor networks (CRSNs) since large energy consumption is required for spectrum sensing and opportunistic access. Medium access control (MAC) is critical for cognitive sensors due to its influence on energy-consuming transceivers. This work proposes a short preamble cognitive MAC (SPC-MAC) protocol for CRSNs. The major contribution of SPC-MAC is the smart combination of short preamble sampling and opportunistic forwarding. As a result, SPC-MAC could support reliable and fast spectrum access while reducing energy consumption. Furthermore, SPC-MAC is a distributed cognitive MAC protocol without requiring any common control channels. The protocol modeling for SPC-MAC is performed rigorously. Analytical and simulation results validate the superior performance of SPC-MAC.**

***Index Terms*—Cognitive radio sensor network, MAC protocol, opportunistic forwarding, preamble sampling.**

I. Introduction

Wireless sensor network (WSN) has been recently expected to be integrated into the Internet of Things [2]-[4] which provide enormous connections of devices and sensors with different applications, such as assisted living, industrial automation, smart manufacturing, logistics, smart grid, e-health facilities and more [5]. WSNs are generally designed to work on the unlicensed ISM band. With proliferation of wireless networks, the spectrum scarcity issue of the ISM band is becoming critical. Cognitive radio [6]-[8] provides one prospective solution to alleviate spectrum scarcity via exploiting opportunistic spectrum access schemes to circumvent coexisting interferences on the ISM band. By combining cognitive radio and WSNs seamlessly, cognitive radio sensor network (CRSN) has become one important subject in the fields of cognitive radio networks and WSNs [9]-[11].

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Unlike typical WSNs, CRSNs work on licensed channels [9]-[11]. In order to enable opportunistic spectrum access, CRSNs have to conduct spectrum sensing to target vacant channels, and to design cognitive access schemes to sufficiently protect primary users (PUs). Different from cognitive radio networks [6]-[7], CRSNs inherit inherent limitations of WSNs whose capabilities (for example, power, computation and communication) are strictly limited due to constrained energy supply and low-cost hardware.

Up to now, lots of works have been done to CRSNs from the aspects of spectrum sensing, spectrum management, medium access control (MAC), clustering, routing, cross-layer design and so on [12]-[28]. MAC design is critical among the numerous contributions on CRSNs [12]-[28], because of its strong impact on the transceivers of cognitive sensors (CSs). The major challenge for designing CRSN MAC protocols is to efficiently regulate the opportunistic transmission of CSs, while guaranteeing PUs' priority access to licensed channels [22]-[28].

In this work, a short preamble cognitive MAC (SPC-MAC) protocol is proposed. One feature of SPC-MAC is preamble sampling which supports duty cycling of CSs. In doing so, all CSs independently select their sleep/wakeup schedules. CSs can work with a very low duty cycle. Another key aspect of SPC-MAC is opportunistic forwarding that reduces retransmissions due to channel errors by exploiting multiple forwarders. By innovatively combining short preamble sampling and opportunistic forwarding, SPC-MAC supports reliable and fast spectrum access while addressing the energy conservation problem in CRSNs. Furthermore, SPC-MAC is a distributed cognitive MAC protocol without requiring any common control channels (CCCs), which renders it desirable to typical CRSNs. Potential applications of SPC-MAC are envisaged in the area of smart grid sensor networks [20] [21] [28]. We also perform the rigorous protocol modeling for SPC-MAC. Specifically, energy consumption, throughput, and energy efficiency of SPC-MAC are analyzed in detail. Analytical and simulation results validate the superior performance of SPC-MAC.

The remainder of this work is organized as follows. Section II gives a literature review. Section III presents the network model. Section IV proposes the SPC-MAC. Section V performs analytical modeling to the proposed SPC-MAC. Section VI conducts simulations to demonstrate the effectiveness of SPC-MAC. Section VII draws conclusions. To facilitate the reading of readers, a list of frequently used acronyms is given in Table I.

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TABLE I
FREQUENTLY USED ACRONYMS

Acronyms	Description
CRSN	Cognitive Radio Sensor Network
MAC	Medium Access Control
SPC-MAC	Short Preamble Cognitive MAC
CRB-MAC	Receiver-based MAC Protocol for CRSNs
CS	Cognitive Sensor
PU	Primary User
CS-TX	CS Transmitter
CS-RX	CS Receiver
CCC	Common Control Channel
HDS	Hop Distance to the Sink
ACK	Acknowledgement

II. RELATED WORK

A. *Spectrum Sensing & Management*

In [12], sleeping and censoring parameters of cooperative spectrum sensing (CSS) schemes in CRSNs are optimized to minimize energy consumption subject to the sensing performance constraint. In [13], the selection of optimal sensing CSs is incorporated in the sensing optimization framework of [12]. In [14], a novel energy efficiency optimization problem for CSS schemes is formulated. A heuristic-decomposition-based solution method with verified convergence and efficiency is also devised. In [15], an energy-aware spectrum management method for CRSNs is proposed, wherein the optimal operation mode of CSs is selected based on the POMDP theory. In [16], a spectrum assignment problem in CRSNs under constraints such as coverage and power budget is formulated as a mixed integer nonlinear programming whose optimal solution is obtained in polynomial time by relaxation methods. In [17], the joint spectrum sensing and random access control problem in CRSNs is formulated as a network utility maximization (NUM) problem subject to the constraints of energy consumption and detection probability. One distributed algorithm with guaranteed convergence is proposed to solve the NUM problem. In [21], a cross-layer management method for CRSNs is proposed to cope with hostile RF environments in smart grid applications. A recent survey [11] summarizes the spectrum management schemes for CRSNs.

Notice that, previous works in CRSNs [11]-[17], [21] mostly focus on designing energy-aware optimization methods to CRSNs, while contributions on cognitive MAC protocols are neglected.

B. *MAC Protocol*

In [22], a cluster-based MAC (KoN) protocol is proposed. KoN enables CSs in clusters to have contention free communications and defines a channel-choosing mechanism to regulate inter-cluster communications. In [23], a packet reservation multiple access based MAC (PRMA-MAC) protocol is proposed. PRMA-MAC proposes a novel frame structure to support the combination of slotted ALOHA, TDMA and reservation scheme. In [24], a cognitive adaptive MAC (CA-MAC) protocol is proposed. CAMAC employs a small number of CSs to conduct spectrum sensing and adaptively updates sensing duration to reduce energy consumption. In [25], a hybrid cognitive MAC protocol is proposed. Its hybrid nature embodies in the aspects of TDMA-based centralized coordination function and CSMA/CA-based distributed coordination function. In [26], an ENC-MAC protocol which improves spectrum efficiency based on a dedicated CCC approach is proposed. There is one thing in common for [22]-[26], i.e, a dedicated CCC is assumed. However, the centralized MAC protocols relying on the CCC are infeasible for many CRSN scenarios, due to the channel saturation issue or strong spectrum dynamics.

Without relying on the CCC, one reservation-based MAC (C2RMAC) protocol for distributed CRSNs is proposed. However, C2RMAC is only available to the case of single-hop networks with perfect synchronization among CSs. In [28], a receiver-based MAC protocol for CRSNs (CRB-MAC) is proposed. Preamble sampling is employed by CRB-MAC to reduce idle listening and support duty cycling. In addition, CRB-MAC adopts opportunistic forwarding with multiple receivers to improve the transmission reliability along with reducing retransmissions. However, CRB-MAC has two main drawbacks. First, prior to transmitting one data packet, CSs have to send a long preamble to activate neighboring CSs. Consequently, an extra waiting period to receive the packet is raised. Second, all neighboring CSs have to be involved in the forwarding process. Therefore, large energy consumption for the CRSN is inevitable.

Similar to [28], the proposed SPC-MAC protocol is also a distributed MAC protocol that relies on preamble sampling and opportunistic forwarding to support low-duty-cycled CRSNs. However, SPC-MAC has the following novelties in comparison to CRB-MAC [28].

- First, with short preamble sampling each CS transmitter (CS-TX) could reduce energy consumption in sending preambles and only one eligible CS receiver (CS-RX) responds to it once receiving its short preamble. In this way, SPC-MAC can remarkably reduce delay and energy consumption during the wake-up and transmission process.
- Second, in SPC-MAC each CS-TX encodes the network address and hop distance to the sink (HDS) into its short preambles. In doing so, only the first waking up CS-RX who is with a smaller HDS than the CS-TX will forward packets. As a result, idle listening and the complex coordination of forwarders in CRB-MAC can be avoided by SPC-MAC, which implies that the delay and energy consumption in the forwarding process can be further reduced.

III. NETWORK MODEL

A CRSN consisting of one sink and M CSs (denoted by $\mathbf{M} := \{1, 2, ..., M\}$) is considered. As shown in Fig. 1, the CRSN is fully covered by a primary network. This work considers convergecast traffic, i.e., data packets are generated at CSs and transmitted to the sink via single hop or multiple hops. We have one licensed channel which can be used by CSs when PUs are inactive. Each CS works in the half-duplex mode. The local time at each CS may be different. We remove the assumption on one dedicated CCC in [22]-[26] since centralized cognitive MAC protocols relying on

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dedicated CCCs are not always feasible in the context of CRSNs. In contrast, we aim to seek for a lightweight MAC protocol amenable to distributed implementation, by which each CS can make its channel access decision independently.

The PU activities over the licensed channel can be modeled as an independent and identically distributed (i.i.d) stochastic process with busy and idle states. Let P_b and P_i denote the probabilities of the facts that the licensed channel are busy and idle, respectively. Obviously, we have $P_b + P_i = 1$.

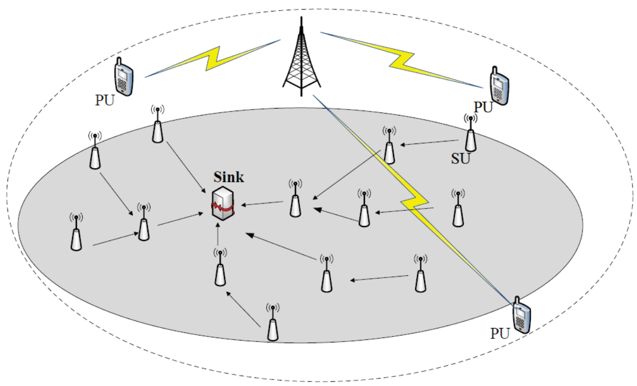

Fig. 1. The network architecture of the CRSN

Next, we define frame structures for CS-TXs and CS-RXs. As shown in Fig. 2, every CS-TX works in a frame-by-frame manner. The frames of CS-TXs are with duration T. A sensing phase, a spectrum access phase and a sleep phase are explicitly defined in each frame. First, CS-TXs are required to carry out spectrum sensing for protecting the PUs. If CS-TX i ($i \in \mathbf{M}$) targets a vacant channel, it will compete to access the channel in the spectrum access phase; otherwise, goes to the sleep phase. Let $T_a^{(i)}$ and $T_d^{(i)}$ denote the durations of the spectrum access phase and the sleep phase for CS-TX i, respectively. $(T_s^{(i)}, T_a^{(i)}, T_d^{(i)})$ may be different across frames. However, $T = T_s^{(i)} + T_a^{(i)} + T_d^{(i)}$ is fixed. In order to track the dynamics of PUs, the frame duration T cannot be very large (T is set 200ms in this work).

The time of CS-RXs is divided into frames. The frames of CS-RXs are with duration T_{RX}. As shown in Fig. 3, the frame structure of a CS-RX is also composed of three phases, including a preamble sampling phase, a receiving data phase and a sleep phase. At the beginning of each frame, the CS-

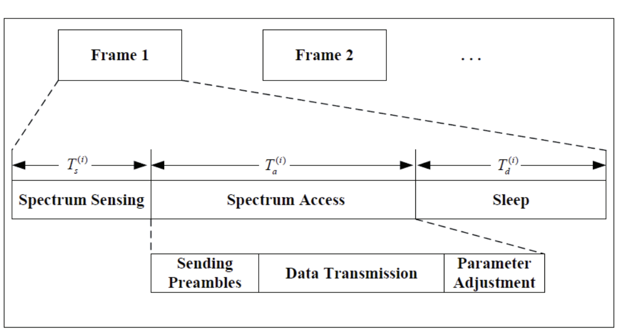

Fig. 2. Frame structure of each CS-TX

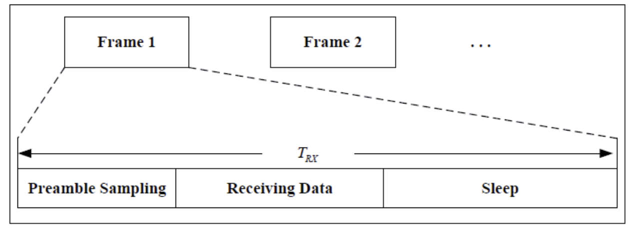

Fig. 3. Frame structure of each CS-RX

RX carries out preamble sampling. If the CS-RX receives preambles which are destined for it, it will commence the receiving data phase and receive data from its dedicated CS-TX; otherwise, goes to the sleep phase.

IV. SPC-MAC DESIGN

In the following we illustrate three crucial steps of SPC-MAC and later give its protocol description.

A. Spectrum Sensing

All CSs adopt energy detection as the spectrum sensing technique. CS i ($i \in \mathbf{M}$) compares its received energy E over a licensed channel with a pre-specified threshold ε_i. Let H_0 and H_1 denote the PUs are absent and present on the licensed channel, respectively. Then, the spectrum sensing problem at CS i can be formulated as a binary hypothesis problem:

$$\text{sensing decision} = \begin{cases} H_0, & \text{if } E < \varepsilon_i \\ H_1, & \text{if } E \geq \varepsilon_i. \end{cases} \quad (1)$$

Sensing performances are usually measured by false alarm ($P_f^{(i)}$) and detection probabilities ($P_d^{(i)}$). The primal signal is an i.i.d. complex PSK modulated signal with 0 mean and σ_u^2 variance, and the noise at each CS receiver is a circular symmetric complex Gaussian signal with 0 mean and σ^2 variance. Assuming that the primary signal and the noises are independent, we achieve $P_f^{(i)}$ and $P_d^{(i)}$ [7]:

$$P_f^{(i)} = Q\left(\left(\frac{\varepsilon_i}{\sigma^2} - 1\right)\sqrt{T_s^{(i)} f_s}\right) \quad (2)$$

and

$$P_d^{(i)} = Q\left(\left(\frac{\varepsilon_i}{\sigma^2} - \gamma_i - 1\right)\sqrt{\frac{T_s^{(i)} f_s}{2\gamma_i + 1}}\right), \quad (3)$$

where γ_i denotes the SNR of the primary signal at CS i. f_s denotes the sampling frequency of CSs. $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty} \exp(-t^2/2)dt$ is the complementary distribution function of standard Gaussian.

In order to mitigate energy consumption in spectrum sensing, SPC-MAC uses an adaptive sensing approach [24] which has been proved effective in protecting PUs with low energy consumption.

B. Short Preamble Sampling

Short preamble sampling is adopted to support low-duty-cycled CRSNs. As a result, all CSs select their sleep/wakeup schedules independently. Each CS sleeps for most of its time and wakes up every T_{RX} to detect ongoing transmissions on the licensed channel. To avoid the deafness of CS-RXs, the CS-TX transmits a series of short preambles prior to the data packet. In order to guarantee that the preambles of CS-TX can always be received by CS-RXs, the preamble duration of CS-TXs T_p is set larger than T_{RX}.

Similar to X-MAC [29]-[30], this work inserts small pauses between short preambles, during which the CS-TX stops to listen to the medium. These pauses enable one eligible[1] CS-RX to send an early acknowledgment (ACK) to the CS-TX, notifying the CS-TX that one eligible CS-RX is ready to receive its data.

With short preamble sampling, each CS-TX reduces energy consumption in sending preambles and only one eligible CS-RX responds to the CS-TX once receiving its short preamble. In this way, SPC-MAC significantly reduces the overhead in terms of delay and energy consumption during the wake-up and transmission process.

Remark 1: As in SPC-MAC one CS-TX may have multiple eligible receivers, it will sometimes result in the collision of early ACKs. However, we claim that the collision of early ACKs can be neglected in SPC-MAC, due to the fact that all CSs are asynchronous and work with very low duty cycles.

C. Opportunistic Forwarding

Unlike X-MAC [29]-[30], in SPC-MAC a CS-TX does not define a particular receiver. Instead, any CS-RX has chances to be a forwarder of the CS-TX, which remarkably reduces retransmissions in SPC-MAC by exploiting the broadcast nature of wireless medium. As all CSs in the communication range of the CS-TX can receive the preambles, we require the CS-TX to encode its network address and HDS[2] in each short preambles to avoid cycles. To be specific, according to the decoded information from the short preamble, one CS will decide to forward the data if it has a smaller HDS than the received HDS (hereafter referred to as the forwarding condition), and goes to sleep, otherwise. The CS-RXs meeting the forwarding condition are called "eligible".

Different from CRB-MAC [28] that makes use of a complex coordination process among multiple forwarders, SPC-MAC requires only one eligible CS-RX responding to the CS-TX earliest to forward the packet. In doing so, the forwarding process of SPC-MAC is dramatically simplified, and as a result delay and energy consumption during the forwarding process can be further reduced.

The CS-TX will discard the packet and go to sleep if it receives an ACK from the CS-RX. Otherwise, the CS-TX will retransmit the packet until the maximum number of retransmissions is reached or an ACK is received.

[1]The term "eligible" will be explained in Section IV. C.

[2]We assume that each CS is aware of its HDS through network layer exchange.

D. Protocol Description

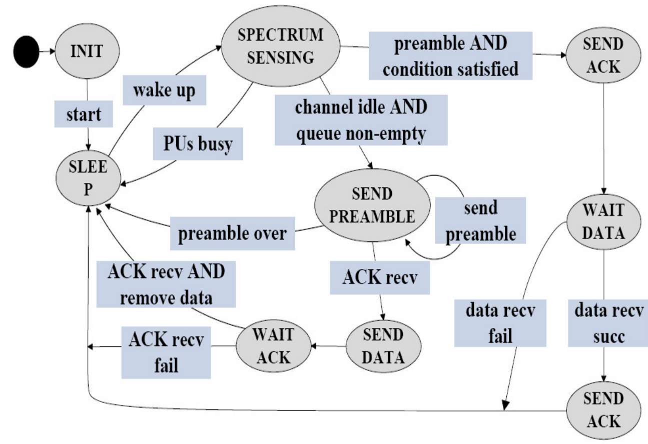

Fig. 4. SPC-MAC phase transition diagram

Fig. 4 demonstrates the state transition of SPC-MAC phases. Specifically, each loaded CS-TX starts its frame by spectrum sensing. If CS-TX i ($i \in \mathbb{M}$) determines the absence of PUs, its SPC-MAC commences the data transmission phase; otherwise, CS-TX i goes to sleep for the rest of the frame. CS-TX i transmits a series of short preambles, each of which includes the network address and the HDS of CS-TX i. Each CS-RX periodically listens to the wireless medium. CS-RX i decodes the received short preamble and replies an ACKto notify CS-TX i that it is ready to receive data if its HDS is smaller than that of CS-TX i. After that, CS-TX i transmits one data packet to CS-RX i and CS-RX i acknowledges CS-TX i by replying an ACK if the data packet is correctly received. Since then, CS-TX i and CS-RX i go to sleep until the coming frame. In the multi-hop transmission, the same operation repeats until the sink receives the data.

Fig. 5 illustrates a successful transmission for SPC-MAC. CS S first targets an idle licensed channel by spectrum sensing and transmits short preambles. CS C decodes the preambles earliest and goes to sleep since its HDS is larger than that of CS S. CS A is an eligible receiver and successfully receives the packet of CS S. Although CS B is also eligible, it declares a busy channel and goes to sleep.

Fig. 6 illustrates a failed transmission for SPC-MAC. Due to the mis-detection, CS S starts to transmit short preambles after spectrum sensing, which leads the transmission collision between CS S and PUs. As a result, none of forwarders can decode the corrupted preambles and immediately go to sleep. As CS S cannot detect collisions while transmitting preambles, it completes the transmission of short preambles and then waits for one short preamble duration to receive the ACK. Obviously, the ACK cannot be received by CS S. Then, CS S will infer that its transmission is unsuccessful due to collisions.

From the above discussion, we conclude that with SPC-MAC each CS mitigates collisions over the licensed channel independently. Thus, SPC-MAC is a distributed cognitive MAC protocol without requiring CCCs.

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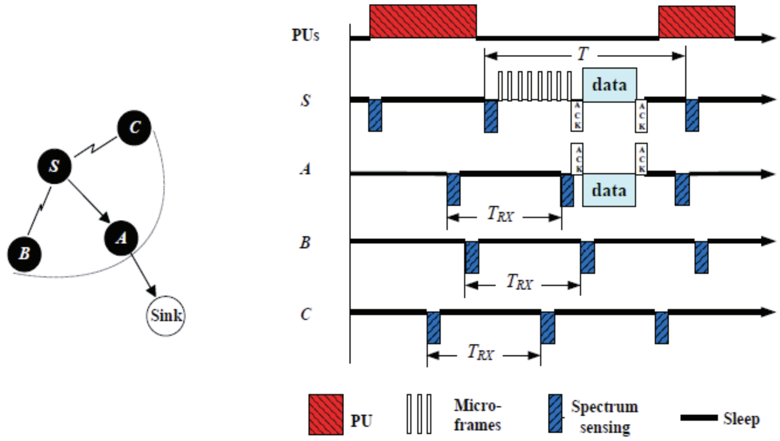

Fig. 5. A successful transmission for SPC-MAC

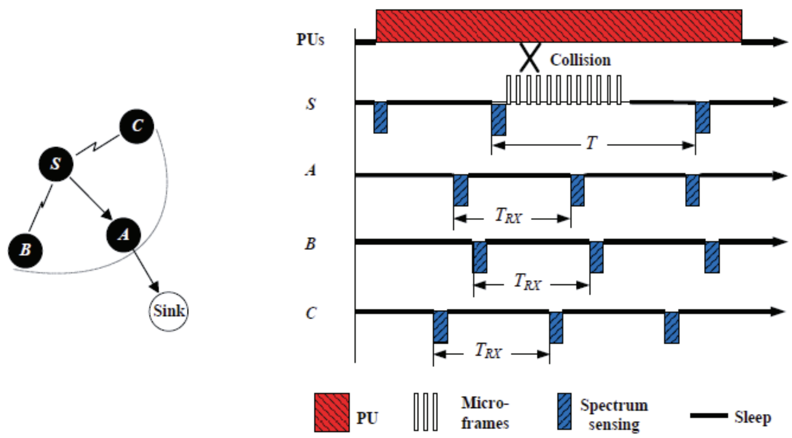

Fig. 6. A failed transmission for SPC-MAC

V. Analytical Modeling

Let P_{sw} be the probability of accessing the licensed channel. P_{sw} is calculated according to the following cases: (1) the licensed channel is busy and mis-detection happens; (2) the licensed channel is idle and false alarm does not happen. Then, we have

$$P_{sw} = P_b(1 - P_d) + P_i(1 - P_f). \tag{4}$$

A. Energy Consumption

In SPC-MAC, the probability of a failed single transmission on the licensed channel (P_{fail}) depends on the corruption in short preamble, ACK and data. Let m, a and d denote the sizes of short preamble, ACK and data, respectively. Then, P_{fail} is given as follows

$$P_{fail} = P_{sw}\left(1 - (1-p)^{m+2a+d}\right), \tag{5}$$

where p denotes the bit error rate.

Let r_m denote the quantity of short preambles. Notice that, the transmitter will transmit one short preamble and wait for an ACK interchangeably. For notational convenience, we assume the durations of one short preamble and an ACK are the same (denoted as T_m). Thus, r_m, given by $r_m = \lceil \frac{T_p}{2T_m} \rceil$, also denotes the number of pauses in the preamble. As only one receiver will respond to the transmitter and its responding time of an ACK is uniformly distributed during the preamble phase, the average number of transmitted short preambles and pauses is $\frac{r_m}{2}$.

On the transmitter side, energy consumptions in a successful (E_T_{succ}) and failed transmission (E_T_{fail}) can be derived. Specifically, for a single successful transmission, the probability of the event that one short preamble, two ACKs and the data frame are successfully decoded is given by $(1-p)^{m+2a+d}$. For a single failed transmission, the probability calculation has to consider two cases: (1) link establishing fails (short preamble or ACK); (2) transmission fails (data frame or ACK). Then, we have E_T_{succ} and E_T_{fail} as shown in (6) and (7), respectively. Notice that, P_t and P_r denote the transmit power and the receive power, respectively. Let E_{ss} denote the energy consumption in spectrum sensing. Let P_s denote the spectrum sensing power. Then, we have $E_{ss} = (\tau + T_s)P_s$, where τ is the transition time between different modes.

On the receiver side, we can similarly derive energy consumptions of receivers in a successful (E_R_{succ}) and failed transmission (E_R_{fail}). Notice that, the CSs detect preambles during spectrum sensing when PUs are inactive. We have

$$E\_T_{succ} = E_{ss} + P_{sw}(1-p)^{m+2a+d}\left(\left(\frac{1}{2}r_mT_m + T_d\right)P_t + \left(\frac{1}{2}r_mT_m + T_m\right)P_r\right), \tag{6}$$

$$\begin{aligned} E\_T_{fail} =& E_{ss} + P_{sw}\left(\left(1-(1-p)^{m+a}\right)\frac{1}{2}r_mT_m(P_t+P_r)+\right. \\ & \left.(1-p)^{m+a}\left(1-(1-p)^{a+d}\right)\left(\left(\frac{1}{2}r_mT_m + T_d\right)P_t + \left(\frac{1}{2}r_mT_m + T_m\right)P_r\right)\right). \end{aligned} \tag{7}$$

$$E\_R_{succ} = E_{ss} + P_{sw}(1-p)^{m+2a+d}\left(2T_mP_t + T_dP_r\right) \tag{8}$$

$$\begin{aligned} E\_R_{fail} =& E_{ss} + P_{sw}\left((1-p)^m\left(1-(1-p)^a\right)T_mP_t + (1-p)^{m+a}\left(1-(1-p)^d\right)(T_mP_t + T_dP_r)\right. \\ & (1-p)^{m+a+d}\left(1-(1-p)^a\right)(2T_mP_t + T_dP_r)). \end{aligned} \tag{9}$$

E_R_{succ} and E_R_{fail} as shown in (8) and (9), respectively.

Suppose that one CS-TX has N eligible receivers. In SPC-MAC, as only one CS receives the data, the energy consumption in a successful transmission $E\_R_{N\_succ}$ should account for all possible scenarios in which only one CS receives the data correctly. Specifically, we assume the $(N-i+1)$th wake-up CS correctly receives the packet. In this case, we should account for the energy consumption for the $(N-i+1)$th wake-up CS (i.e., $E_{R_{succ}}$) and the energy consumption for the first $(N-i)$ wake-up CSs (i.e., $(N-i)E_{R_{fail}}$) which fail in receiving the packet. The rest of the $(i-1)$ CSs are still in sleep and thus their energy consumptions are not included. Finally, we calculate $E\_R_{N\_succ}$ as follows

$$E\_R_{N\_succ} = \frac{\sum_{i=1}^{N}\binom{N}{i}\left(E\_R_{succ} + (N-i)E\_R_{fail}\right)}{\sum_{i=1}^{N}\binom{N}{i}}. \tag{10}$$

The energy consumption in a single transmission when N receivers cannot receive the packet correctly is

$$E\_R_{N\_fail} = N \cdot E\_R_{fail}. \tag{11}$$

When a transmission fails, the CS-TX will perform retransmission. Next, we will derive the retransmission model for SPC-MAC. Let P_a denote the probability that one CS-TX will successfully transmit the data after a successive failures. Thus, P_a is given by

$$P_a = (P_{fail})^{aN}\left(1-(P_{fail})^N\right). \tag{12}$$

Then, the mean number of retransmissions prior to success is calculated as follows:

$$\mathcal{X} = \sum_{a=1}^{Z} aP_a, \tag{13}$$

where Z denotes the maximum number of retransmissions.

Let $\mathcal{X}_{ss}$ denote the expected number of sensing events for transmitting over the licensed channel. Then, we have

$$\begin{aligned} \mathcal{X}_{ss} &= \sum_{i=1}^{\infty} i\left(1-P_{sw}\right)^i P_{sw} \\ &= \left(\sum_{i=1}^{\infty}(1-P_{sw})^i + \frac{\mathcal{X}_{ss}(1-P_{sw})}{P_{sw}}\right)P_{sw} \\ &= (1-P_{sw})(1+\mathcal{X}_{ss}) \end{aligned}$$

and then

$$\mathcal{X}_{ss} = \frac{1-P_{sw}}{P_{sw}}. \tag{14}$$

Based on (13) and (14), the energy consumption of SPC-MAC over single hop is

$$\begin{aligned} E_{SPC} =& \mathcal{X}(E\_T_{fail} + E\_R_{N\_fail}) + \\ & E\_T_{succ} + E\_R_{N\_succ} + \mathcal{X}_{ss}E_{ss}. \end{aligned} \tag{15}$$

B. Throughput

Based on (13) and (14), the single hop delay and throughput of SPC-MAC over the licensed channel are respectively given by (16) and

$$Th_{SPC} = \frac{d}{D_{SPC}}. \tag{17}$$

C. Energy Efficiency

Energy efficiency has been widely used to characterize the CRSN performance [14]. With E_{SPC} and Th_{SPC}, we obtain the energy efficiency of SPC-MAC over the licensed channel as follows

$$EE_{SPC} = \frac{\text{Thoughput}}{\text{Energy consumption}} = \frac{Th_{SPC}}{E_{SPC}}. \tag{18}$$

VI. Simulations

This section verifies the single hop and multi-hop performances of the SPC-MAC by comparing it with CRB-MAC [28] and CAMAC [24]. Table I summarizes parameter values which describe typical CRSN settings [7] [14] [28].

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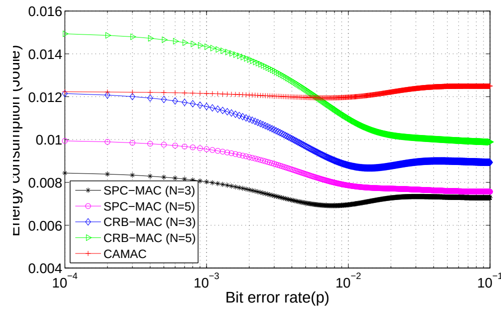
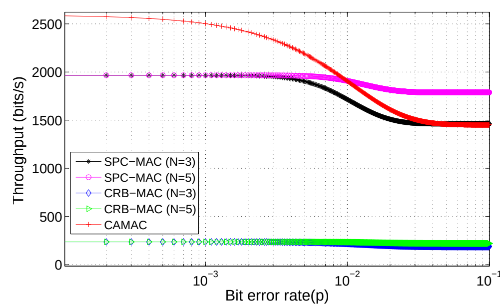
$$D_{SPC} = \mathcal{X}\left((1-(1-p)^{m+a})r_m T_m + (1-p)^{m+a}(1-(1-p)^{a+d})\left(r_m T_m + T_d + T_m\right)\right) + \frac{T_{pr}}{2} + T_d + T_m + \mathcal{X}_{ss}(\tau + T_s) + T_{RX}(\mathcal{X}_{ss} - 1) \quad (16)$$

TABLE II
PARAMETER VALUES

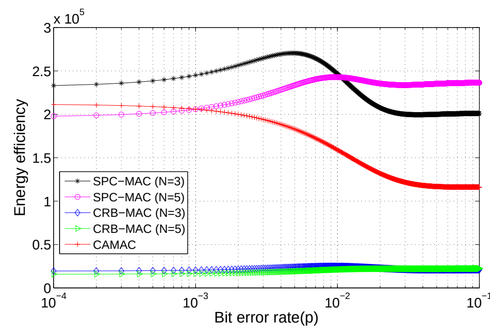
Symbol	Meaning	Value
ω	lower bound of detection probability	0.9
M	number of CSs	20
γ_i	SNR of the primary signal at CSs	-15dB
ε_i	detection threshold	1.05
P_b	occurrence probability of the PU	{0.1, 0.2, . . ., 0.6}
$T_s^{(i)}$	spectrum sensing slot for CSs	20ms
τ	transition time between two different modes	88.4μs
P_t	transmit power of CS	66.16mW
P_r	receive power of CS	70.69mW
P_s	spectrum sensing power of CS	65.83mW
T_p	preamble duration	144ms
T	frame duration of CS-TXs	200ms
T_{RX}	frame duration of CS-RXs	144ms
T_d	one data packet duration	4ms
T_m	one short preamble duration	40μs
Z	maximum number of retransmissions	7
m	size of one short preamble	24 bits
d	size of one data packet	100 bits
a	size of one ACK	24 bits



(a) Energy consumption



(b) Throughput



(c) Energy efficiency

Fig. 7. Single hop performance evaluation

A. Single Hop Performance

Fig. 7 shows single hop analytical performances of SPC-MAC under different bit error rates p ($P_b = 0.4$). Besides, we also analyze the performance of SPC-MAC by setting two values of N (i.e., 3 and 5).

For energy consumption (Fig. 7(a)), SPC-MAC dominates CRB-MAC and CAMAC obviously for all values of p. That is due to the fact that with short preamble sampling CS-TXs could reduce energy consumption in sending preambles and only one eligible CS-RX forwards data. In contrast, in CRB-MAC each CS-TX keeps transmitting preambles for the whole preamble phase and all CS-RXs in the neighborhood of the CS-TX will be involved in the forwarding process. We also notice that both MAC protocols increase energy consumption when N grows (i.e., more CS-RXs are involved in the receiving, forwarding and retransmission phases). CAMAC suffers the largest energy consumption since it does not support duty-cycling.

For throughput (Fig. 7(b)), the advantage of SPC-MAC over CRB-MAC is overwhelming. Due to the long preamble and duration of contention window, CRB-MAC suffers the large delay (or low throughput). Different from CRB-MAC, SPC-MAC takes half of the preamble phase on average to wake up one CS-RX, which also avoids the complex process of selecting forwarders. Noticeably, the throughput gain of SPC-MAC over CRB-MAC is more than 9 in condition of small p. Similar to Fig. 7(a), in Fig. 7(b) both SPC-MAC and CRB-MAC improve throughput as N increases because of high probability of successful transmission. On the other hand, CAMAC outperforms SPC-MAC by avoiding delay in preambles when N is small. However, for large N, CAMAC is dominated by SPC-MAC when p is large, since reliability improvement by space diversity compensates the throughput loss by preambles.

For energy efficiency (Fig. 7(c)), SPC-MAC again outperforms CRB-MAC, which directly follows the previous superior performance of SPC-MAC over CRB-MAC. Different from Fig. 7(b), SPC-MAC outperforms CAMAC when $N = 3$ for all p and $N = 5$ for large p (i.e., $p > 10^{-3}$), and is dominated by CAMAC when $N = 5$ for small p.

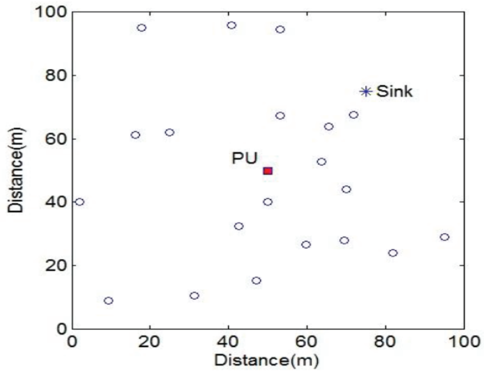


Fig. 8. Simulated topology

B. Multi-hop Performance

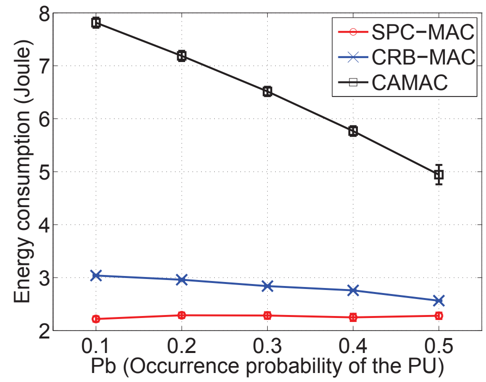
We arbitrarily generate one CRSN with twenty randomly deployed CSs, one sink and one PU. Fig. 8 shows the CRSN topology, with circles, the star and the square denoting CSs, the sink, and the PU, respectively. Communication radii of all CSs are 30m and the CRSN is within the communication range of the PU. The channel error rate p is 10^{-2}.

Fig. 9 presents multi-hop performances of the compared MAC protocols under different occurrence probabilities P_b. We perform 100 independent simulations and each simulation lasts 200s. During each simulation, 10^3 packets are non-uniformly produced by different CSs. The simulations are conducted by OMNeT++ [31]. In the following, comparison results will be produced by the batch mean method for the confidence level 95%.

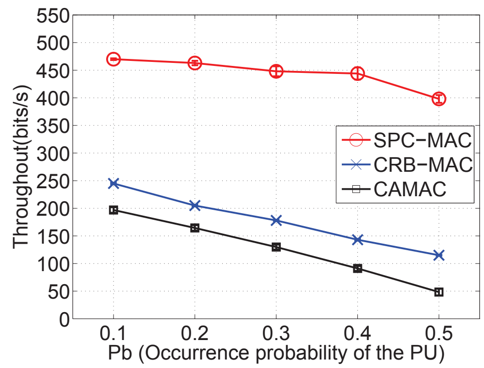
Fig. 9(a) shows the comparison in energy consumption defined as the consumed energy summation of all CSs. For fair comparison, the physical layer of each CS is specified as [28]. It is shown in Fig. 9(a) that CAMAC is the worst in terms of energy consumption among the three MAC protocols due to the lack of duty-cycling and SPC-MAC remarkably dominates the other two MAC protocols. Specifically, SPC-MAC consumes only 73.5% of the energy consumption by CRB-MAC for $P_b = 0.1$. This is because each transmission in CRB-MAC involves multiple potential forwarders, which incurs large energy consumption especially when the occurrence probability of PU is small (e.g., $P_b < 0.5$).

Fig. 9(b) shows the comparison in network throughput measured by the ratio of received bits by the sink to the simulation duration. Obviously, due to large communication overhead in the control channel, CAMAC has the lowest throughput among the three MAC protocols. Again, SPC-MAC has a significant improvement in throughput in comparison to CRB-MAC. Specifically, the largest throughput gain of SPC-MAC is 3.2 for $P_b = 0.5$. The throughput gain attributes to the short preamble sampling that sharply reduces the average duration of transmitting packets. Different from Fig. 9(a), it is shown in Fig. 9(b) that the throughputs of all the compared MAC protocols monotonically decrease with respect to P_b. The observation directly follows that large P_b reduces secondary transmission opportunities.

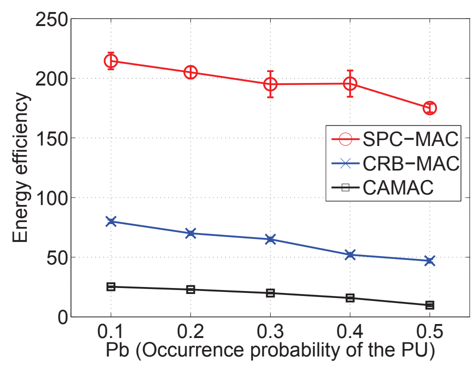
Fig. 9(c) presents the comparison on the energy efficiency.



(a) Energy consumption



(b) Throughput



(c) Energy efficiency

Fig. 9. Multi-hop performance evaluation

The results in Fig. 9(c) are straightforward from the definition of energy efficiency in (18). Specifically, the largest energy efficiency gain of SPC-MAC is 3.8214 when P_b=0.4.

VII. Conclusion

An SPC-MAC for CRSNs supporting opportunistic access and conserves energy has been proposed. With the short preamble sampling CSs have been working with a very low duty cycle, while with opportunistic forwarding SPC-MAC has reduced retransmissions due to channel errors. In addition, without relying on a CCC, SPC-MAC is quite suitable for distributed CRSNs. Analytical and simulation results have validated the superior performance of SPC-MAC.

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In the near future, we will evaluate the overall delay metric of SPC-MAC by incorporating more protocol parameters. In the long term, we will generalize this work to design a multi-channel MAC for CRSNs.

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