SPC-MAC: A Short Preamble Cognitive MAC Protocol for Cognitive Radio Sensor Networks

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***Abstract*—Cognitive radio has been widely recognized as a promising solution to reliable and time-efficient wireless sensor networks. However, cognitive capability requires an extra energy consumption in spectrum sensing and spectrum access, which imposes a rather challenging problem to low cost sensors. This paper proposes a short preamble cognitive medium access control (SPC-MAC) protocol which supports reliable and fast spectrum access while addressing the energy conservation problem in cognitive radio sensor networks (CRSNs). The novelty of SPC-MAC lies in the combination of short preamble sampling (for supporting low duty cycling in CRSNs) and the opportunistic forwarding (for reliable and fast transmission). Because of the self-organizing nature, SPC-MAC does not require a common control channel. Extensive simulations demonstrate the advantage of SPC-MAC over existing works in terms of energy consumption and throughput.**

I. Introduction

Wireless sensor networks (WSNs) have received considerable attentions in recent years for their immense potentials in the applications of environment monitoring, battlefield reconnaissance, biomedical observation and industrial automation [1]-[4]. Traditional WSNs usually operate on the license-exempt 2.4 GHz industrial, scientific and medical (ISM) band. With the fast proliferation of wireless technologies, the 2.4 GHz ISM band is getting overcrowded and the spectrum congestion problem is becoming more critical for WSNs than ever before. In this situation, it is very hard to maintain a given level of quality of service. One promising solution is to exploit opportunistic spectrum access approaches via cognitive radios (CRs) [5]-[6] to circumvent the coexisting interference over the 2.4 GHz ISM band. As a smart combination of CR and WSN, cognitive radio sensor network (CRSN) is recently considered as one of the most attractive topics in the fields of both CR networks and WSNs [7]-[9].

Different from traditional WSNs, CRSNs work on licensed bands and periodically sense the bands, determine the vacant channels, and access them to collect source information [7]-[9]. To achieve this, CRSNs have to perform spectrum sensing besides the information collection, and to design access schemes which produce no (or strictly limited) interference to primary users (PUs). On the other hand, unlike CR networks [5]-[6], CRSNs inherit the fundamental limitations of traditional WSNs whose lifetime and capabilities (e.g., computation, communication and storage) are strictly limited due to constraints in energy resources and low-cost hardware. Among the numerous research branches in CRSNs [10]-[24], the medium access control (MAC) protocol design is crucial, due to its influence on the transceiver which is the most energy-consuming component of a cognitive sensor (CS). To sum up, the MAC protocol of CRSNs has to arbitrate the opportunistic spectrum access of CSs to the licensed bands in an energy-efficient way, while guaranteeing the priority access of PUs [10]-[24]. However, the contributions on the design of practical MAC protocols for CRSNs are very limited [19]-[24].

In [19], Xu et al. propose a cluster-based MAC (KoN-MAC) protocol for multi-hop CRSNs. In KoN-MAC, nodes in each cluster enjoy contention free communications and a channel-choosing scheme is proposed to reduce the collision of inter-cluster communications. In [20], Jamal et al. propose a multi-channel MAC for CRSNs, which employs an asynchronous duty cycle approach for channel acquisition and data transmission. In [21], G. A. Shah et al. propose a CSMA-based cognitive adaptive MAC (CAMAC) protocol. CAMAC performs spectrum sensing only when nodes have data for transmission and runs duty cycling during the idle period to conserve energy. In [22], Anamalamudi et al. propose an energy-efficient hybrid CR-MAC protocol with TDMA-based synchronized control channel and CSMA-based directional data transmission to reduce energy consumption due to link access overhead, multi-channel hidden terminal, deafness, and spectrum mobility. In [23], B. Kim et al. propose an energy-efficient non-overlapping channel MAC (ENC-MAC) for CRSNs. The common drawback of [19]-[23] lies in the assumption of one common control channel (CCC). Such an idealistic and dedicated CCC may not be always available in the context of CRSNs, and it also suffers from the control channel saturation problem.

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In [24], Aijaz et al. propose a cognitive receiver-based MAC (CRB-MAC) protocol for CRSNs. Without relying on the CCC, CRB-MAC employs the preamble sampling technique for duty-cycled asynchronous WSNs to avoid idle listening and exploits opportunistic forwarding technique to improve transmission reliability. However, CRB-MAC has two major disadvantages. First, before each packet transmission a long preamble has to be sent to wake up all neighboring CRSN nodes, as a result of which a large waiting time for receiving the packet is raised. Second, each neighboring CRSN node has to receive the broadcast packet, which leads large energy consumption and coordination overhead during the forwarding phase.

Inspired by CRB-MAC [24], this paper proposes a short preamble cognitive medium access control (SPC-MAC) protocol for CRSNs. With the smart combination of short preamble sampling and opportunistic forwarding, SPC-MAC supports reliable and fast spectrum access while addressing the energy conservation problem in CRSNs. The novelties of SPC-MAC can be summarized as follows:

- First, with short preamble sampling each CS transmitter reduces energy consumption in preambles and one eligible CS receiver responds to it as soon as receiving its short preamble. As a result, SPC-MAC significantly reduces the overhead in terms of latency and energy consumption during the wake-up and transmission process.
- Second, in SPC-MAC each CS transmitter encodes the network address and hop distance from the sink (HDS) into its short preambles, and only the first waking up CS receiver that is with a smaller EDS compared with the CS transmitter will be selected to forward packets. In this way, ineligible receivers as well as the coordination of forwarders can be eliminated by SPC-MAC, as a result of which the latency and energy consumption during the forwarding process can be further reduced.
- Finally, similar to [24], SPC-MAC does not require a CCC for message exchange despite of superior network performance, which is extremely appealing to typical CRSNs.

II. Network Model

We consider an ad-hoc CRSN which consists of one sink and a set of static M CSs, $\mathbf{M} := \{1, 2, ..., M\}$, and is located in the same area with a primary network. J licensed bands are opportunistically available for the CRSN, i.e., the CRSN can accesses the licensed bands only when PUs are inactive. In the CRSN, data can be generated for some online monitoring or control applications. The proposed SPC-MAC considers such application scenarios. Each CS generates data (periodic or non-periodic) to the sink (which is also known as convergecast traffic). The local clocks at different CSs may be different. Seeking for a lightweight ad hoc networking, each CS makes independent channel access decisions without central scheduling. In doing so, the assumption on the network-wide CCC by existing works [19]-[23] can be removed in this paper.

The PU activity for the j-th ($1 \leq j \leq J$) licensed band is formulated as an independent and identically distributed (i.i.d) stochastic process with two states (i.e., busy and idle). The busy period and the idle period are exponentially distributed variables with means of $1/\mu_{ON}^j$ and $1/\mu_{OFF}^j$, respectively. Then, the probabilities of the facts that the j-th licensed band are busy and idle are respectively given by

$$P_b^j = \frac{\mu_{OFF}^j}{\mu_{OFF}^j + \mu_{ON}^j} \text{ and } P_i^j = \frac{\mu_{ON}^j}{\mu_{OFF}^j + \mu_{ON}^j}.$$

Obviously, we have $P_b^j + P_i^j = 1$.

III. SPC-MAC Design

With the aim of supporting opportunistic spectrum access, SPC-MAC requires CSs to perform spectrum sensing ahead of spectrum access. In order to conserve energy and accelerate packet forwarding, SPC-MAC integrates the short preamble sampling with the opportunistic forwarding scheme.

This section first illustrates three key steps of SPC-MAC and then gives out the protocol operation of SPC-MAC.

A. Spectrum Sensing

Energy detection is the most suitable spectrum sensing technique for CRSNs because of its simplicity of hardware implementation and low signal processing cost. Without loss of generality, each CS adopts energy detection as the spectrum sensing technique. The MAC frame structure in the CRSN consists of a sensing slot (T_s) and a transmission slot (T), as shown in Fig.2. For notational convenience, we neglect the user index and consider the spectrum sensing to an arbitrary licensed band j.

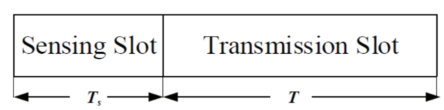


Fig. 1. Frame structure of the CRSN

Each CS compares the received energy E over the target band j with a specified detection threshold ε. Let H_0 and H_1 denote the absence and presence of PUs on the target licensed band j, respectively. Then, the spectrum sensing problem at each CS can be formulated as a binary hypothesis problem

$$\text{Sensing decision} = \begin{matrix} H_0, \text{ if } E < \varepsilon \\ H_1, \text{ if } E \geq \varepsilon. \end{matrix} \qquad (1)$$

Spectrum sensing can be characterized by the probabilities of false alarm and detection, denoted as P_f^j and P_d^j, respectively. Assuming that the primal signal is an i.i.d. complex PSK modulated signal with zero mean and σ_u^2 variance, and the noise at each CS is a circular symmetric complex Gaussian signal with zero mean and σ^2 variance, both of which are independent of each other, we according to [6] obtain P_f^j and P_d^j as follows:

$$P_f^j = Q \quad \frac{\varepsilon}{\sigma^2} - 1 \quad \overline{T_s f_s} \qquad (2)$$

and

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

where ε and γ are the energy detection threshold and the signal to noise ratio of PU signals at the CS, respectively. f_s denotes the sampling frequency of the CS. $Q(x) = 1/\sqrt{2\pi}\int_x^{+\infty}\exp(-t^2/2)dt$ is the complementary distribution function of the standard Gaussian.

It is clearly shown from (2) and (3) that large T_s gives higher confidence to the PU detection, but at the same time results in an increased energy consumption. To this end, we adopt the adaptive sensing scheme [21] in which the spectrum sensing period dynamically varies between fast sensing and fine sensing based on the rule of multiplicative increase and linear decrease. It is shown in [21] that the adaptive sensing scheme can protect PU sufficiently with reduced energy consumption.

For a given T_s, the optimal transmission slot T_j that maximizes the throughput of the CRSN subject to the interference constraint $IR_j < IR_{max}^j$ can be achieved by studying optimal sensing framework in [5], where IR_j and IR_{max}^j denote the interference ratio (expected fraction of ON duration of PU transmission interrupted by the transmission of CSs) and the maximum tolerable interference ratio on the j-th licensed channel, respectively. Specifically, we have

$$IR_j = (1 - P_d^j)P_b^j + P_i^j(1 - P_f^j) + e^{-\mu T_j}(P_f^j - P_d^j), \quad (4)$$

where $\mu = \max(\mu_{ON}^j, \mu_{OFF}^j)$. Then, the optimal transmission slot T_j is given by [5]

$$\begin{aligned} T_j =& \mu^{-1}[\ln P_i^j - \ln(P_i^j\omega + P_b^j(1-\omega) - IR_{max}^j) \\ & + \ln(2\omega - 1)], \end{aligned} \quad (5)$$

where ω denotes the detection probability threshold (close to but less than 1) which is specified by the regulator.

B. Short Preamble Sampling

SPC-MAC adopts short preamble sampling to enable duty cycling in CRSNs. In the short preamble sampling approach, each CS selects its sleep/wakeup schedule independently of other CSs. The CSs spend most of their time in sleep mode and wake up every T_{CI} to check an ongoing transmission. To avoid deafness of CS receivers (CS-RX), the CS transmitter (CS-TX) first transmits a series of short preambles before the data packet on one licensed band. In order to ensure that the preambles of CS-TX can always be heard by CS-RXs, the preamble phase duration of CS-TXs T_p is set larger than T_{CI}.

Similar to X-MAC [25]-[26], this paper inserts small pauses between the series of short preambles, during which the CS-TX pauses to listen to the medium. The preamble phase consists of multiple micro-frames, and each of micro-frame lasts T_m. Without loss of generality, we assume the pause duration is the same as T_m. These gaps enable one eligible CS-RX to send an early acknowledgment (ACK) packet back to the CS-TX, which indicates the CS-TX that one eligible CS-RX is ready for receiving 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 as soon as receiving its short preamble. As a result, SPC-MAC significantly reduces the overhead in terms of latency and energy consumption during the wake-up and transmission process.

C. Opportunistic Forwarding

Different from X-MAC [25]-[26], in SPC-MAC a CS-TX does not define a particular CS as its receiver. Notice that, in SPC-MAC any eligible CS-RX has chances to forward the packets of the CS-TX, which significantly reduces retransmission of SPC-MAC by using the broadcast nature of wireless channel. As all the neighboring nodes within communication range of the CS-TX can receive the preambles, we require the CS-TX encodes its network address and HDS in each short preamble to avoid cycles. Specifically, based on the decoded information from the short preamble, each individual CS decides to forward the data if it has a smaller HDS compared to the received HDS (the CS-RX is called "eligible"), and returns to sleep immediately, otherwise.

Unlike CRB-MAC [24] which defines a complex coordination process among multiple forwarders, SPC-MAC requires only one eligible CS-RX who responds to the CS-TX earliest to forward the packet. In this way, the forwarding process of SPC-MAC is significantly simplified, and thus the latency and energy consumption during the forwarding process can be further reduced.

The CS-TX will discard the packet and return 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 reaches or an ACK is received.

D. Protocol Operation

Specifically, each loaded CS-TX starts the frame by local spectrum sensing based on energy detection. If the sensing result of CS-TX i ($i \in \mathbf{M}$) indicates the absence of PUs, its SPC-MAC commences the data transmission phase; otherwise, CS-TX i returns to sleep for the rest of the frame. In order to mitigate collisions with other CS-TXs, CS-TX i will defer its transmission for a random time period Δ_i, which is uniformly distributed in $[0, f(q_i)]$ ms, where $f(q_i)$ denotes a monotonic decreasing backoff function of the data queue length q_i of CS-TX i. When the time duration Δ_i expires, CS-TX i then performs carrier sensing to check whether the licensed band is occupied by other CS-TXs. If carrier sensing indicates an idle band, CS-TX i transmits a series of short preambles, each of which includes the network address and the HDS of CS-TX i. Otherwise, CS-TX i returns to sleep. Each CS-RX periodically listens to the medium. CS-RX i decodes the received short preamble and sends an ACK to notify CS-TX i that it is ready for receiving data if its HDS is smaller than that of CS-TX i. Subsequently, CS-TX i transmits the packet to CS-RX i and CS-RX i acknowledges CS-TX i by sending an ACK if the packet is correctly received. After that, both CS-RX i and CS-RX i return to sleep until the start of their next frames.

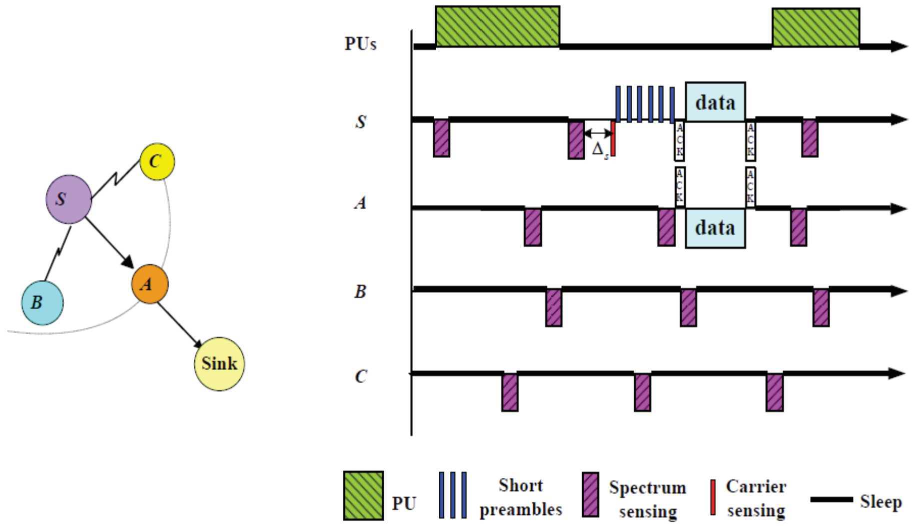


Fig. 2. Schematic of SPC-MAC: successful transmission

Fig. 4 presents the schematic of SPC-MAC for a successful transmission. CS S first detects a vacant licensed band and transmits a series of short preambles. CS C decodes the preambles earliest and returns to sleep immediately for the purpose of reducing overhearing cost since its HDS is larger than that of CS S. CS A is an eligible receiver and successfully receives the packet of CS S. Though CS B is also eligible, it detects that the channel is busy and returns to sleep immediately.

Notice that, all CSs independently operate on the licensed bands and their ways of mitigating collisions are fully distributed. Therefore, the proposed SPC-MAC does not rely a CCC, which renders SPC-MAC extremely desirable for CRSNs. Potential applications of the SPC-MAC presented in this paper are envisaged in the area of smart grid sensor networks [17] [18] [24].

IV. SIMULATIONS

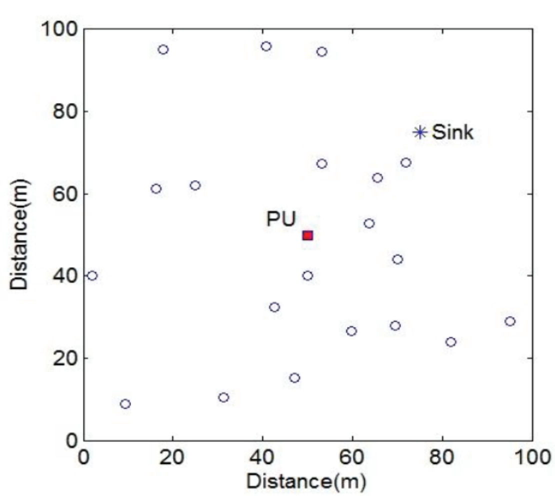


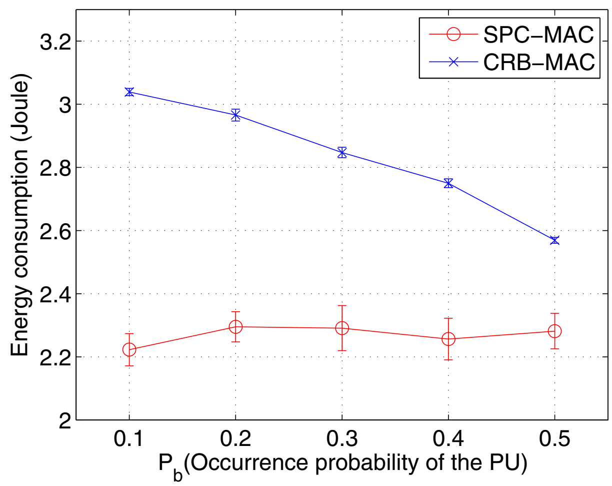
Fig. 3. Simulated topology (mean density=2×10^{-3}nodes per unit area)

TABLE I
PARAMETER VALUES USED IN THE SIMULATIONS

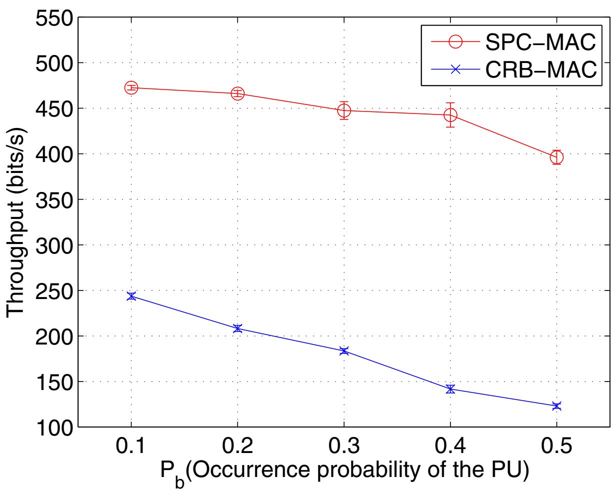
Symbol	Meaning	Value
ω	detection probability threshold	0.9
μ_{OFF}	busy state parameter of the PU	2
μ_{ON}	idle state parameter of the PU	3
IR_{max}	maximum interference ratio	0.25
M	number of CSs	20
γ	signal to noise ratio of PU signals at CSs	-15dB
P_b	occurrence probability of the PU	{0.1, 0.2, 0.3, 0.4, 0.5, 0.6}
T_s	spectrum sensing slot for CSs	20ms
T	transmission slot for CSs	180ms
T_p	preamble duration of CS-TXs	144ms
T_{CI}	checking interval for CSs	144ms
ε	detection threshold	1.05
f_s	sampling frequency	200KHz
$f(q_i)$	backoff function of the data queue length q_i of CS-TX i	$10\exp\left(-0.5(q_i+1)\right)$

This section verifies the performance of the proposed SPC-MAC protocol. We simulate a moderate CRSN with 20 Poisson distributed CSs, one sink and one PU. The simulated network topology is given in Fig. 5, where circles denote CSs, the star denotes the sink, and the square denotes the PU. The whole CRSN lies in the coverage area of the PU. The communication radius of each CS is 30 units. All parameters in the simulations are summarized in Table I, representing values describing typical CR and WSN scenarios, following, e.g., [6] [13] [24]. The simulations are conducted by OMNeT++ [27].

To the best of our knowledge, CRB-MAC [24] is the unique CCC-free cognitive MAC protocol for CRSNs. Next, we will compare the proposed SPC-MAC with CRB-MAC. For fair comparison, simulation results are generated based on the method of batch means with 100 independent simulation runs for the confidence level of 90%. We set each simulation duration as 200s during which 10^3 packets from different CSs are generated. In order to reflect the heterogeneity of CSs, we simulate the scenario in which the traffics at different CSs are non-uniformly distributed.



(a) Energy consumption



(b) Throughput

Fig. 4. Performance evaluation

Fig. 6(a) compares SPC-MAC and CRB-MAC in the energy consumption metric which is measured as the sum of energy consumption of each CS. For fairness, we specify the physical layer of CSs according to [24]. The sensing power, the receive power and the transmit power of CSs are set 70.69mW, 65.83mW, and 66.16mW, respectively. Each short preamble includes 24 bits and each ACK includes 24 bits. All data packets are with the same packet-size of 100 bits. Fig. 6(a) shows that SPC-MAC significantly outperforms CRB-MAC, where the largest energy saving (26.5%) happens when $P_b = 0.1$. This can be explained by the fact that each transmission of one CS in CRB-MAC requires the participation of many forwarders due to the broadcast nature of wireless channel, which is very energy consuming especially when the PU is less active (e.g., $P_b < 0.5$).

Fig. 6(b) presents the comparison on the end-to-end throughput of network between SPC-MAC and CRB-MAC. The end-to-end throughput is defined as the ratio of received bits by the sink to the simulation duration. A large value of throughput implies the efficient use of the licensed channel. Again, SPC-MAC has an obvious throughput improvement over CRB-MAC, with the largest throughput gain 3.2 when $P_b = 0.5$. The reason for this observation lies in the short preamble, which help reduce the total transmission time of packets. Unlike Fig. 6(a), Fig. 6(b) shows that both SPC-MAC and CRB-MAC are monotonic decreasing in P_b, which stems from the fact that large P_b reduces the transmission opportunities of CSs.

V. Conclusion

This paper has proposed an SPC-MAC protocol which supports opportunistic spectrum access while addressing the energy conservation issue in CRSNs. The novelty of SPC-MAC lies in the combination of short preamble sampling and opportunistic forwarding with the consideration of PU protection. Furthermore, SPC-MAC does not rely on a CC-C, which makes SPC-MAC more appealing for distributed CRSNs than existing centralized MAC protocols. Simulations have demonstrated the advantages of SPC-MAC over CRB-MAC in terms of energy consumption and throughput.

Future work will focus on protocol analysis and the implementation of SPC-MAC on real CRSN platforms.

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