Cognitive Adaptive Medium Access Control in Cognitive Radio Sensor Networks

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***Abstract*—Spectrum sensing is an integral part of medium access control (MAC) in cognitive radio (CR) networks as its reliability determines the success of transmission. However, it is an energy-consuming operation that needs to be minimized for CR sensor networks (CRSNs) due to resource scarcity. In this paper, a cognitive adaptive MAC (CAMAC) protocol, which supports opportunistic transmission while addressing the issue of power limitation in CRSNs, is proposed. Energy conservation in CAMAC is achieved in three fronts: on-demand spectrum sensing, limiting the number of spectrum sensing nodes, and applying a duty cycle. Spectrum sensing is initiated on-demand when the nodes have data to transmit, and it also exploits a subset of spectrum sensing nodes to gather spectrum availability information for all the nodes. Furthermore, it defines an adaptive duty cycle for the CRSN nodes to periodically sleep and remains awake when data are available for transmission. Hence, CAMAC stands as an adaptive solution that employs the small number of spectrum sensing nodes with an adaptive sensing period yielding minimum energy consumption. Simulation results reveal the efficiency of CAMAC in terms of high throughput and less energy consumption, which is adaptive to primary users' traffic and duty cycle.**

***Index Terms*—Cognitive radio, medium access control (MAC), spectrum correlation, wireless sensor networks (WSNs).**

I. Introduction

THE WIDELY growing need for spectrum allocation, underutilization of the existing licensed spectrum, and cost of the licensing spectrum have forced the development of cognitive radios (CRs). The emergence of CRs has influenced the design of many existing and evolving wireless networks to exploit its dynamic nature of the scarce spectrum access. Users of wireless networks, which are exclusively allocated a certain licensed spectrum, are the primary users (PUs) of that spectrum. On the other hand, users of CR networks, which access the spectrum dynamically and avoid interfering with the PU transmission, are the secondary users (SUs). With these capabilities, the SU can operate in any of the licensed and unlicensed bands. Prior to its transmission, the CR must first perform the spectrum sensing operation to detect the potentially vacant bands, regardless of the PU transmission. Among the detected vacant bands, it then decides which is the most appropriate for transmission and finally adapts its transceiver so that the opportunistic transmission can take place over the new channel.

Wireless sensor networks (WSNs) are characterized by the communication and resource-constrained devices, and traditionally, they employ a low-power communication standard such as IEEE 802.15.4 that operates on unlicensed fixed spectrum. The unlicensed spectrum has become saturated due to the coexistence of various emerging networking standards, particularly IEEE 802.11, Bluetooth (IEEE 802.15.1), and WSN itself. It is therefore imperative to exploit the dynamic spectrum access techniques in WSNs by employing CRs, hence giving birth to the CR sensor networks (CRSNs) [1]. CRSNs are envisioned to be deployed in the environment that experiences frequent changes in spectrum characteristics, such as monitoring and surveillance in transport vehicles, in which CR allows the nodes to intelligently configure their transmission parameters under the varying propagation conditions of mobile vehicles. CRSNs can be particularly used in industrial sensor networks, which have recently been proposed for smart grid applications [28], and their performance is investigated for various application domains of smart grid in [29]. Thus, CR in WSNs brings not only intelligence in the spectrum utilization to overcome coexistence issues but noise mitigation as well.

In addition to bringing the potential benefit of opportunistic transmission, CRs introduce many new research issues in CRSNs. The realization of CRSNs requires incorporating the dynamic spectrum access techniques efficiently in the communication protocols of resource-constrained sensor nodes. There is an urgent need for designing a new medium access control (MAC) protocol that closely interacts with the physical layer to determine the spectrum holes and transmits on them efficiently. Hence, the simple carrier sensing operations in MAC are overridden by the spectrum sensing, negotiation, and switching operations, making it a challenging task.

A great deal of research is carried out for MAC protocols in WSNs; however, they are not adaptive to dynamic spectrum access and inevitably inapplicable in CRSNs. The aggregate interference of a cognitive network is studied in [25], but it does not propose any multiple access technique. Although a number of MAC protocols are proposed for *ad hoc* CR networks [4], [5], [9], they mainly focus on providing sensing efficiency but do not consider the energy constraints in their design.

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Recently, spectrum sensing algorithms [13]–[15] have proposed for CRSNs, and also, the performance of transport protocols is studied in [17]. Nevertheless, CRSNs are mainly an unexplored field, and to the best of our knowledge, this is the first attempt at designing a MAC protocol for CRSNs.

This paper addresses the problem of MAC in CRSNs and proposes a carrier sensing multiple access (CSMA)-based cognitive adaptive MAC (CAMAC) protocol. CAMAC follows the dynamic spectrum access paradigm to provide opportunistic transmission while addressing the issue of power limitation in CRSNs. In particular, the main features of CAMAC are as follows. First, the spectrum sensing is initiated on-demand when the nodes have data. Second, it uses an adaptive sensing period that varies between fast sensing and fine sensing, where the fine sensing requires larger sensing period that is computed by characterizing the arrival of PUs and their traffic. Third, it limits the number of spectrum sensing nodes by exploiting the spatial correlation of densely deployed sensor nodes and formulates the distortion in correlated spectrum detection probability. Thus, a small number of spectrum representative (SR) nodes sense the spectrum, and the outcomes of sensing are shared by the nearby nodes for transmission. Fourth, it limits the overhead incurred in CSMA techniques for transmission of small-size packets commonly observed in sensor networks. Finally, it implements an adaptive duty cycling technique that provides a tradeoff between energy saving and delay caused in sleep mode.

The remainder of this paper is organized as follows. Section II discusses the related work in CR networks. Section III presents the network and radio model along with the assumptions. In Section IV, we describe the CAMAC protocol in detail. Performance evaluation and results are provided in Section V, and finally, we conclude this paper in Section VI.

II. Related Work

This section investigates the existing work on spectrum sensing that has influence on the design of a MAC protocol in CRSN and MAC protocol for CR *ad hoc* networks whose solutions can be potentially considered in CRSN.

A compressed distributed spectrum sensing algorithm [13] is proposed for CRSN considering the energy limitation of sensor nodes. It defines a wideband sampling structure and the required sampling rate equivalent to the bandwidth of a single subband, which is much lower than the existing schemes. This simple structure is convenient for implementation in the resource-constrained CRSN, but consideration to the sensing duration is not explored. In [14], a cooperative spectrum sensing scheme for CRSN determines the upper and lower bounds for cooperation in spectrum sensing to achieve sensing and energy efficiency. However, the cooperation does not exploit the spatial correlation of nodes to minimize spectrum sensing operations. Spectrum sensing in [15] is also proposed for CRSN, which is based on a spatially decaying time-incremental updating algorithm. It is a cooperative sensing algorithm that aims to minimize the overhead messages in sensing, but the sensing itself is not adaptive to minimize energy consumption. An adaptive modulation scheme for CRSN is explored in [16], which aims to maximize the lifetime of a sensor network by adapting different constellation sizes according to the observed channel gain in spectrum sensing. Moreover, reliability and congestion control in CRSN is investigated in [17] to study the performance of existing transport protocols proposed for WSNs. It is observed that the existing transport protocols do not efficiently address the challenges in CRSN since their design does not adhere to the properties of CR environment. Thus, CRSNs are gaining the focus of researchers, and the design of protocols for CRSN is in progress to exploit the potential of CRSNs in real-world applications [18].

Generally, random-access-based MAC protocols are preferred for densely deployed sensor and *ad hoc* networks since they do not require synchronization. Considering the potential of random access techniques in CRSNs, we explore only the CSMA-based MAC protocols for sensor and *ad hoc* networks. The dynamic open spectrum sharing MAC protocol [16] uses three radios, each for control, data, and busy tone. The spectrum bands used for data transfer are mapped to the frequencies in the busy-tone band. Whenever a node transmits or receives data on a given channel, it also emits a busy signal in the corresponding busy-tone band. However, this solution is not practical to implement for CRSNs since it uses multiple transceivers, and busy-tone transmission makes it inefficient for energy-constrained sensor nodes. In [7], a single radio is used for both control and data transmission (DT). It adaptively expands or shrinks the transmission spectrum according to the bandwidth needs. Moreover, it uses frequency-division multiplexing to bring efficiency by using different bands for transmission and reception. However, it incurs high overhead in sensing and negotiating two different bands and does not consider the energy efficiency in its operations.

HC-MAC [5] uses a single transceiver and also defines an optimal stopping rule to limit the sensing for efficient spectrum sensing. However, spectrum negotiation and transmission is based on carrier-sensing-based handshaking algorithm that incurs higher overhead and, therefore, is not suitable for CRSNs. Opportunistic spectrum MAC [8] forms groups of SU nodes and chooses a delegate node in each group. These delegate nodes periodically switch to control the channel to share the channel conditions among them. Then, they propagate the learned information to their group members and determine the suitable data channels (DCs) until the next interval. Since it restricts the group of nodes to use a certain DC based on the statistics collected in the past that limits the advantages of dynamic spectrum access. Moreover, it introduces excessive overhead in sharing the channel statistics.

In general, the existing protocols do not define the duty cycle for the nodes to conserve the energy consumed in idle listening, which is mandatory for sensor networks. Moreover, sensor nodes are usually densely deployed that provides a great deal of opportunity to exploit the spatial correlation of nodes in spectrum sensing. None of the proposed MAC protocols consider such an opportunity for energy-efficient sensing, which is the primary goal in CRSNs. To the best of our knowledge, this is the first MAC protocol proposed for CRSNs that integrates the dynamic spectrum access technique with the energy-efficient design of a MAC.

III. Network and Radio Model

Let N be the total number of sensor nodes deployed in the field $X \times Y$ and r be the transmission range of sensor nodes. Nodes are presumably deployed uniformly, the density of nodes (ρ) is found to be $N\pi r^2/X \times Y$. Here, we assume density as the nodes per coverage area instead of unit area to simplify the derivation. We assume that the nodes are location-aware, either by employing GPS receivers or running some localization algorithm. We assume that sensor nodes employ a single transceiver for control and DTs. We also assume that nodes use a network-wide common control (CC) channel that is known for control signaling.

CC is always available to the SU nodes, with which the PUs do not interfere. Recently, the guard band is also suggested for allocation of CC channel [21]. We also assume that the CC jamming issues are either not present or can be mitigated by dynamically allocating the CC using cross-channel communication [26] and frequency hopping [27]. Usually, the CC channel has limited bandwidth and supposedly remains available throughout the network lifetime. To simplify the design of MAC and reduce the control overhead, we assume that slotted ALOHA is used to access CC that also evades the synchronization of sensor nodes. Moreover, there are M DCs, which are accessed in a distributed manner, and there is no central node to collaborate the scheduling of channels dynamically.

Let P_t^x be the transmitted signal power by a PU x, the signal power received by a sensor node i (P_r^i) can be obtained as

$$P_r^i = C_{\text{ref}} \frac{P_t^x}{d(x,i)^\alpha} \tag{1}$$

where $d(x,i)$ is the distance between PU x and sensor node i. C_{ref} is the rest of all other common factors affecting the received signal strength, which is computed by using Friis transmission equation as $G_t G_r (\lambda/4\pi)^2$ [23]. G_t and G_r are taken to be the mean effective gain of the antennas. In addition, it might also incorporate path loss variation depending on the propagation environment, which could be a random variable having a lognormal distribution about the mean distant-dependent value [24]. Here, we assume that the sensor nodes are homogeneous and deployed in the field that has similar propagation conditions. α is the propagation constant taking value in [2] and [4], depending on the deployment field.

IV. Cognitive Adaptive Medium Access Control

Here, we present the design of the proposed on-demand CAMAC protocol for CRSNs. In sensor networks, data could be generated for some event- or query-driven applications. Therefore, all the sensor nodes may not always send data to the application sink. The proposed CAMAC considers such application scenarios, and CR operations are executed on-demand when the nodes have data for transmission. Similarly, spectrum sensing is adaptively performed with variable sensing period that changes according to the failure and success of transmission on a particular spectrum hole, as described in Section IV-A. Energy is further conserved by exploiting spatial correlation of nodes' spectrum measurements (SMs), in which a node sensing spectrum becomes the SR node, and its sensing results are used for nearby nodes to avoid an energy-consuming sensing task. Moreover, variable distributed duty cycles are scheduled to limit energy consumption in overhearing, as discussed in Section IV-D. Table I lists the most common parameters used in the following sections.

TABLE I
Variables and Their Definitions

Symbol	Definition
δ	Spectrum sensing time slot
κ	Integer multiple of spectrum sensing
z	Maximum integer multiple for fine sensing
T_x	Maximum transmission period of a SU
τ_i	Frame period of node i
T_{of}	PU idle period
μ_{of}	PU mean idle period
ϵ_z	Threshold of successful SU transmission
ϵ_f	Threshold of false sensing probability
CW	Contention window size
RTT	Round trip time
τ_{idle}	Maximum idle period of a node in active state

A. CAMAC Spectrum Sensing Algorithm

CAMAC employs the proposed adaptive spectrum sensing algorithm in which the spectrum sensing period dynamically varies between the lower and the analytically determined higher bound. The sensing interval is adjusted according to the reliability of spectrum sensing results and energy consumption. In CRs, transmission is always preceded by a spectrum sensing operation that helps in determining the activity of both PUs and SUs. Spending more time in sensing gives higher confidence to the user detection decision and, thereby, decreases the chances of interference. On the other hand, higher sensing time results in lesser transmission opportunity and, eventually, lower throughput. Hence, the energy consumed per bit transmission also increases, which is against the fundamental design of a MAC protocol for CRSNs. It is, therefore, imperative to devise an efficient sensing strategy that enhances the throughput of the channel with minimum energy consumption in CRSN.

For efficient dynamic spectrum access, we use adaptive sensing that fluctuates between *fast sensing* and *fine sensing* to adapt to the PU behavior. In *fast sensing*, the sensing period is short to reduce the sensing overhead time, but the sensing results are less reliable, increasing the false channel detection probability. *Fine sensing* uses the long sensing period to reduce the false channel detection probability and eventually minimizes the interference to PU transmission. There are many other factors that might cause transmission failure in CR networks. In [25], the aggregate interference of a cognitive network is studied, which accounts for the sensing procedure, secondary spatial reuse protocol, and environment-dependent conditions such as path loss, shadowing, and channel fading. These factors always remain present in traditional fixed spectrum transmission as well, which are not peculiar to the dynamic spectrum access, except for the sensing procedure. However, in this paper, we are mainly concerned with the transmission interference with the PU due to sensing inaccuracy and follow the overlay approach for spectrum access.

Let δ be the basic spectrum sensing time unit, and a node performs sensing for a duration of an integer multiple κ of δ on all the channels independently, where $1 \leq \kappa \leq z$. It is inclined toward *fast sensing* if $\kappa = 1$ (lower) and *fine sensing* when $\kappa = z$ (higher). Since channels may have different varying characteristics, we use different sensing periods for each channel that results in different values of κ. A new wireless regional area network (WRAN) employing CR is standardized as IEEE 802.22 [12] that performs sensing in two steps. First, *fast sensing* is initiated with shorter period. If the channel is sensed idle, then it further performs *fine sensing* in the second step to refine the spectrum information. This two-step spectrum sensing spends more time in sensing because the transmission radius of the WRAN device is larger. Unlike WRAN, our adaptive sensing is performed in a single step with the sensing period adjusted between the limits of *fast* and *fine sensing* according to the success or failure of transmission, which is efficient for short-range transmission in CRSNs.

Let T_x be the maximum transmission period allowed to an SU. The efficiency of an SU in using channel C_i is obtained by $T_x/(T_x + \kappa_i\delta)$ that demonstrates the energy efficiency of the dynamic spectrum access technique in CRSNs. Since T_x and δ are constant values, the value of κ_i is dynamically changed to vary between fine and fast sensing. Initially, a node chooses a random value of $\kappa_i(t)$ in $[1, z]$ at time $t = 0$ for channel C_i and sets its sensing period to $\kappa_i(t)\delta$. It uses *multiplicative increase and linear decrease* to adjust the value of κ_i. For every successful transmission, κ_i linearly decreases, i.e., $\kappa_i(t+1) = \lceil \kappa_i(t) - \omega_s \rceil$, until it reaches the lower limit. On the other hand, it multiplicatively grows on failure of every transmission, i.e., $\kappa_i(t+1) = \lceil \kappa_i(t) \times \omega_f \rceil$, until it reaches the upper limit z. Here, ω_s and ω_f are the scaling coefficients for convergence to *fast* and *fine sensing*, respectively. The choice of these coefficients depends on the interference with PU and spectrum efficiency. By setting higher ω_s, spectrum sensing will sharply converge to fast sensing with lower κ that takes lesser time in sensing the channel, but it is prone to PU interference. Similarly, a higher value of ω_f results in fast convergence to fine sensing by increasing κ rapidly and improving the PU detection to avoid interference. In our design, we set $\omega_s = 1$ and $\omega_f = 2$.

The upper bound z is defined in such a way that the SU should be able to complete its frame transmission. In CAMAC, an SU transmits on a frame-by-frame basis whenever it finds a vacant band, where the frame duration is composed of a sensing period and a data frame transmission period. Let $\tau_i(t)$ be the frame period during which an SU sees an opportunity to transmit on channel C_i at time t, where $\tau_i(t) = \kappa_i(t)\delta + T_x$. If the frame period is longer, then the collision probability with the PU transmission is higher. Therefore, CAMAC determines $\kappa_i(t)$ for which the collision probability is below a certain threshold, which determines the upper limit z of $\kappa_i(t)$. For the sake of simplicity, we represent $\tau_i(t)$ as τ_i and $\kappa_i(t)$ as κ_i.

Assume that the PUs have an exponential on–off traffic model [9]–[11], with the mean duration of ON and OFF denoted by μ_{on} and μ_{off}, respectively. The probability density function of the idle or OFF period (T_{off}) is given by

$$P_{\text{off}}(T_{\text{off}}) = \frac{1}{\mu_{\text{off}}} \exp\left(-\frac{T_{\text{off}}}{\mu_{\text{off}}}\right). \tag{2}$$

Note that a PU has two states idle (OFF) and active (ON), which are mutually disjoint, and their cumulative probability is always 1. If we have given idle probability P_{off} by (2), then the ON probability is $1 - P_{\text{off}}$. The probability that a PU does not arrive or remains idle during the frame period τ_i on channel C_i to complete its transmission can be obtained as

$$\begin{aligned} Pr[T_{\text{off}} \geq \tau_i] &= 1 - \int_0^{\tau_i} \frac{1}{\mu_{\text{off}}} \exp\left(-\frac{T_{\text{off}}}{\mu_{\text{off}}}\right) d(T_{\text{off}}) \\ &= \exp\left(-\frac{\tau_i}{\mu_{\text{off}}}\right). \end{aligned} \tag{3}$$

The maximum SU frame duration is reached at $\kappa_i = z$, and therefore, $\tau_i = z\delta + T_x$. As a result, (3) is rewritten as

$$Pr[T_{\text{off}} \geq \tau_i] = \exp\left(-\frac{z\delta + T_x}{\mu_{\text{off}}}\right). \tag{4}$$

Hence, it can be deduced that the higher the value of z, the lower the probability of the completing frame. We define a probability threshold (ϵ_z) on successful frame transmission such that $Pr[T_{\text{off}} \geq \tau_i] \geq \epsilon_z$. By using (4), we have

$$\epsilon_z \leq \exp\left(-\frac{z\delta + T_x}{\mu_{\text{off}}}\right). \tag{5}$$

Simplifying (5), we obtain the upper limit z for *fine sensing* as

$$z \approx -\frac{\mu_{\text{off}} \log(\epsilon_z) + T_x}{\delta}. \tag{6}$$

Initially, the order of channel sensing is random. However, after each frame period, channel sensing is performed in ascending order of their κ, as outlined in Algorithm 1.

Algorithm 1 Adaptive spectrum sensing algorithm

```
for all c ∈ C do
  κ_c = rand(1, z) //initialize with random value
  sense(c, κ_c)
  if c = BUSY then
    continue //go to the next channel
  else
    flag = transmit()
    if flag = SUCC then
      κ_c = κ_c − ω_s //linear decrease for fast sensing
    else
      κ_c = κ_c × ω_f //multiplicative increase for fine
    end if
  end if
end for
```

B. SR Nodes in CAMAC

Considering the node density in CRSNs, we determine the SR nodes whose spectrum sensing results are exploited by their neighbors to reduce the energy consumption in spectrum sensing. However, this is subject to the reliability of spectrum sensing results, which is analyzed here. If a node n_i detects some spectrum vacancy, then this also holds for node n_j at a certain distance with some decreased detection probability. We assume that spectrum sensing is based on transmitter energy detection [2], [3]. Probability of spectrum detection (P_d) under shadowing and multipath fading channel [2] is formulated as

$$\bar{P}_d = \int_x Q_m(\sqrt{2\gamma}, \sqrt{\lambda}) f_\gamma(x) dx \tag{7}$$

where $Q_m(.,.)$ is a generalized Marcum Q-function, γ is the signal-to-noise ratio (SNR), λ is the energy threshold used by the energy detector, and $f_\gamma(x)$ is the probability density function of SNR under fading.

PU interference is assumed to be additive white Gaussian noise for SUs since they are densely deployed with short communication range, low antenna height, and omnidirectional antenna radiation type. The propagation condition of the PU signal does not significantly change from one sensor node to the nearby sensor node. Therefore, the cumulative effect of the signals received at the SU is assumed to be Gaussian distributed by the central limit theorem [23]. Thus, the value of P_d can be obtained as

$$P_d = Q_m(\sqrt{2\gamma}, \sqrt{\lambda}). \tag{8}$$

Now, assume that γ_i and γ_j are the SNR values of two neighboring nodes n_i and n_j, respectively, where n_i is selected as an SR node that has the detection probability of P_d^i. Here, γ_i is measured by node n_i, whereas γ_j is the estimated value, computed as follows. Since the signal decay is reciprocal to the propagation constant (α) and power of receiver distance according to (1), the SNR of n_j is estimated using γ_i as [22]

$$\gamma_j = K_\vartheta(d_{i,j}) C_{\text{ref}} \frac{\gamma_i}{(d_{i,j})^\alpha} \tag{9}$$

where $K_\vartheta(d_{i,j})$ is the covariance function of the received signal strength at n_i and n_j, $d_{i,j}$ meters apart. The covariance function is assumed to be nonnegative and monotonically decreasing with the distance. We use a power exponential model for correlation since the electromagnetic waves exponentially decay with the distance. We have

$$K_\vartheta(d_{i,j}) = \exp\left(-\frac{d_{i,j}^2}{\theta_d}\right) \tag{10}$$

where θ_d is a scaling factor that controls the relation between the SNR value and distance. Using (10) in (9), we have

$$\gamma_j = C_{\text{ref}} \frac{\gamma_i}{d_{i,j}^\alpha} \exp\left(-\frac{d_{i,j}^2}{\theta_d}\right). \tag{11}$$

This relationship is plotted in Fig. 1 to demonstrate the correlation of the received signal power between nodes n_i and n_j at varying distance. The closer the two nodes are, the higher the correlated SNR is presumed at the neighboring node, and therefore, the more the chances that the SR node exists.

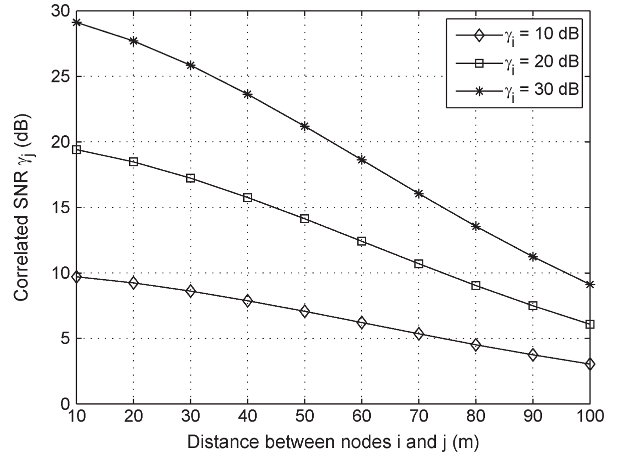

Fig. 1. Correlation of SNR values at different distances between nodes n_i and n_j, where $\theta_d = 10000$.

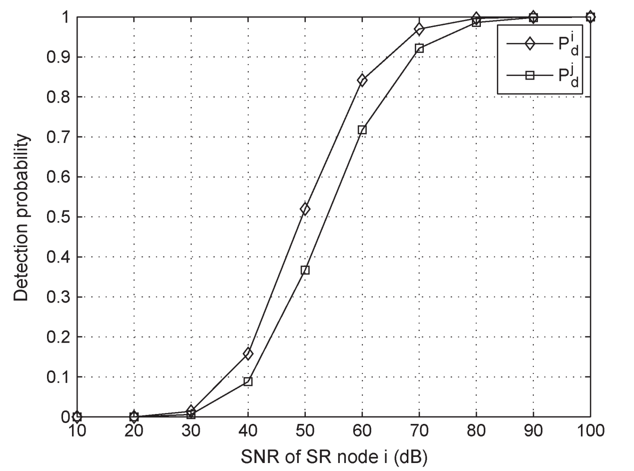

Fig. 2. Detection probability of SR node n_i and correlated node n_j for different SNR values γ_i, where $\theta_d = 10000$, $\lambda = 100$, $\alpha = 2$, and $d_{i,j} = 20$ m.

Ideally, the distance between the PU and the SUs should be exploited in measuring spectrum correlation. Various models (for example, regression model, weighted regression model, etc.) exist in the literature for signal estimation using spatial correlation of other nodes, but they require location information along with their signal measurement. However, SUs do not have information about the location of the PU, and therefore, the distance from the PUs to the SUs cannot be exploited in spectrum estimation. Moreover, the low-power and low-cost design of the sensor nodes does not allow to run very complex and sophisticated algorithms for spectrum sensing. To overcome this problem, we consider the simple scenario, in which the correlated node n_j is assumed to be in line with the SR node n_i. This is reasonable to assume in sensor networks because the nodes are densely deployed with small transmission range, which is evident in Fig. 2, where the difference of PU detection probability is negligible for $10\ \text{db} < SNR < 30\ \text{dB}$ at smaller distance observed in dense deployment of a sensor network. Therefore, the smaller distance would not incur a significant estimation error. This motivates the exploitation of spatial correlation for spectrum sensing in CRSNs.

Hence, the detection probability P_d^j of n_j is obtained by $Q_m(\sqrt{2\gamma_j}, \sqrt{\lambda})$. It can be observed that if node n_i is farther to a PU than n_j, then the signal does not decay and, rather, is amplified at n_j, which increases the false alarm probability. When n_j is closer than n_i, then n_j erroneously estimates decay in signal measured at n_i proportional to its distance to n_i. This results in false detection probability, which is the difference of detection probability $(P_d^i - P_d^j)$ in addition to its false alarm probability, i.e., $P_f^j = P_f^i + (P_d^i - P_d^j)$. The estimated value of P_d^j is a function of SNR value γ_j, which, in turn, is a function of the distance between SR node n_i and correlated node n_j. The higher the distance is, the lower the value of P_d^j is, and eventually, the larger the value of P_f^j is obtained. To restrict the false alarm probability, we define a threshold ϵ_f so that a node exploits the correlation with an SR node if and only if it meets that threshold, i.e., $P_f^j < \epsilon_f$. Fig. 2 shows the detection probability of an SR and a correlated node. It is evident that the difference of probability detection vanishes at a higher SNR value, therefore exploiting correlation saves energy.

C. CAMAC Protocol Operations

The CAMAC protocol operations are performed in three phases: *SM*, *DC contention*, and *DT*. In the SM phase, SUs collect spectrum availability information either by performing spectrum sensing or negotiating with the SR nodes to exploit their spectrum sensing results. Next, the DC contention phase begins, in which nodes use the CC channel for DC negotiation and determine the preferred DCs (PDCHs), and thereafter, the DT phase proceeds, in which nodes use the CSMA approach to transmit data on PDCHs. Apart from these operations, nodes periodically transmit *hello* beacons at low frequency on the CC channel to maintain a *neighborhood* table using the slotted ALOHA random access technique. The *hello* beacon contains the fields *node id*, *residual energy*, and *flag* for SR status. For ease of reference of the task in three phases, we number them in spectrum sensing, channel contention, and transmission with prefixes "S," "C," and "T," respectively. The operations of the protocol for the channel access mechanism are outlined as follows.

1) Spectrum Measurement Phase: When a DT request arrives on occurrence of an event or forwarding, a node n_i commences its transmission operation by first initiating the SM phase to establish a free-channel (FC) list in its vicinity by performing the following tasks.

S1: n_i first looks into the *neighborhood* table for SR nodes. If some SR nodes are found in its *neighborhood* table, then it becomes a spectrum correlating (SC) node and selects the SR node n_j, for which its correlated false alarm probability is lower and meets the threshold ϵ_f, as described in Section IV-B; otherwise, it is obliged to function as an SR node.

S2: It updates its status through the *hello* beacon transmitted after the periodic *hello* interval.

S3: If it becomes an SR node, then spectrum sensing is triggered (see Section IV-A) to find out spectrum holes.

S4: However, if n_i is privileged to be an SC node, it sends a spectrum info request (SI-REQ) to n_j on the CC channel.

S5: n_j replies back with the spectrum info response (SI-RES) message to n_i.

S6: If SI-RES is not received within the timeout period set to roundtrip time in addition to the time slot multiple of its local contention window size, i.e., $TO = RTT + CW \times \delta$, then n_i makes two attempts. If no response is received from n_j, then it continues to try other SR nodes, if they exist. If n_i does not receive SI-RES message from any SR node, then it pronounces itself as an SR node and performs tasks (S2, S3).

2) Channel Contention Phase: Once, a node n_i collects its FC list along with the interference measurements, it starts negotiation of PDCH with the receiver n_k.

C1: n_i first sends a spectrum negotiation request (SN-REQ) to n_k on the CC channel that also includes the list of its FCs in the order of their priority.

C2: If n_k is idle, then it does not immediately reply the spectrum negotiation response (SN-RES) message to n_i and rather initiates its SM phase and sends the REQ-ACK message to acknowledge the request of n_i.

C3: As n_k collects spectrum sensing information, it then sends the SN-RES message that includes the available channels at n_k along with the receiver preferred DC (PDCHr) marked, and thereafter, it switches to PDCHr.

C4: If there does not exist any common FC available to both nodes, then n_j marks the PDCHr to empty, and n_i initializes the SM phase.

3) Data Transmission Phase: Following the successful channel negotiation phase, the sender node n_i gets an opportunity to transmit its data to the next hop node n_k. This phase is rather simple and runs the CSMA technique as follows.

T1: n_i, if it agrees to use the PDCHr channel, sends data frame to n_k. Contrarily, if it does not agree, then it sends its own preferred DC PDCHs to n_k on the PDCHr channel. At this moment, n_k is obliged to switch to the PDCHs channel, and both are tuned to the DC PDCH.

T2: When sensor nodes have a small piece of information or data, it is piggybacked on RTS to avoid the overhead. If it is larger than the RTS threshold, then only RTS is sent.

T3: Similarly, ACK is also piggybacked with the CTS if the frame was RTS-DATA. If the sender does not receive CTS or CTS-ACK, then it retries until it gets the ACK.

T4: If the transmission fails on PDCH, n_i leaves that channel and returns to the channel contention phase.

T5: n_i continues to transmit data until it is present for transmission, and transmission period T_x does not expire; otherwise, it switches to the SM phase.

Fig. 3 demonstrates the state transition of CAMAC phases. As a node gets data for transmission, it starts operating in the SM phase and continues until the FC list gets some entry of a channel. It then moves to the next phase of DC contention and negotiates PDCH with its receiver. As both the nodes are agreed upon some PDCH, the DT phase begins to carry out

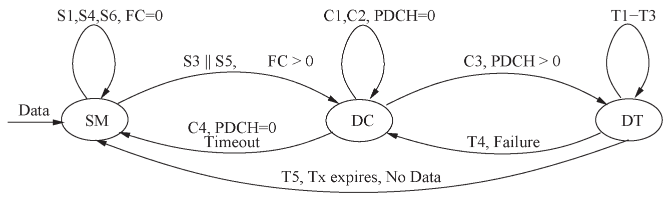

Fig. 3. CAMAC phase transition diagram to illustrate its MAC operations.

transmission of data. A node keeps working in this phase until it has data for transmission, and the transmission period T_x does not expire; otherwise, it moves to the SM phase. In case of failure in transmission, it returns back to the DC phase again to renegotiate the DC.

CAMAC is based on CSMA, in which nodes perform carrier sensing before negotiating access to the medium. Thus, if a channel is in use by a pair of Sus, then other nodes tuning on that channel might not have received the RTS/CTS beacons. This could cause the hidden-node problem. It is not possible to solve the problem entirely with a single transceiver, but the channel negotiation beacons SI-REQ/SI-RES exchanged on the CC channel restrain the overhearing nodes on the CC channel at that instant to not use the channel negotiated in those beacons.

D. Duty Cycling in CAMAC

Unlike fixed-spectrum single-channel MAC, it is challenging to design a duty cycling algorithm for dynamic spectrum access in CRSNs. A distributed duty cycling mechanism is devised for CAMAC, in which nodes define their sleep and wake-up schedule locally without synchronizing with their neighbors. As the sleep period begins, a node turns off its transceiver and starts its expiry timer. However, the event sensing and processing modules keep functioning to acquire event information and process the data for transmission to sink, whereas the spectrum sensing is performed only during the wake-up period. The sleep (T_s) and wake-up (T_w) periods are initially defined proportional to the exponentially distributed ON–OFF periods of PU traffic with probability given in (2) and mean periods of μ_{on} and μ_{off}, respectively. Therefore, at the beginning of each state, we have $T_s = 1/\mu_{\text{on}}$ and $T_w = 1/\mu_{\text{off}}$. To control delay caused due to the sleep period, a node immediately terminates its sleep timer and switches to wake-up mode whenever it detects some event and finds data in its queue. Since the duty cycling is not synchronized, a next hop node can be found in wake-up mode probabilistically with probability $(T_w/T_s + T_w)$ to start its transmission immediately. Similarly, an awake node switches to sleep mode in two cases: The first is when its wake-up timer is expired and transmission buffer is empty; the second is if it was involved in transmission either as a transmitter or a receiver but no frame is transmitted for a certain idle timeout period τ_{idle} but remains in wake-up mode at least for its defined wake-up period, and the timeout period ends thereafter.

A node starts its transmission whenever an event occurs and remains in wake-up state as long as it is either transmitting or receiving data from any of its neighbors. Since an event independently occurs at any time in the field, it is assumed to follow a Poisson traffic model with a mean event occurrence rate of μ_{sen}. For a given node density ρ, the rate at which traffic originates in the transmission range of a node is $\mu_{\text{sen}}\rho$. Thus, the probability density function of a node participating in transmission within the duration of τ_{idle} is

$$P_{tx} = \mu_{\text{sen}} \times \rho \times \tau_{\text{idle}} \times \exp(-\mu_{\text{sen}}\rho\tau_{\text{idle}}).$$

Let P_{next} be the probability of a node being selected by a routing protocol as a next hop node among its neighbors, the probability that a node remains active becomes $P_{tx} \times P_{\text{next}}$. As a result, the duty cycle (η) of a node is obtained as

$$\eta = \frac{T_w + T_s(P_{tx} \times P_{\text{next}})}{T_s + T_w}. \tag{12}$$

Hence, the energy consumption is directly proportional to η. The higher the duty cycle η is, the more energy of a node is consumed, and vice versa. On the other hand, delay is inversely proportional to η, and the increase in delay due to η will be the proportion of $1/\eta$ times the delay without duty cycle.

TABLE II
SIMULATION PARAMETERS USED IN DIFFERENT SCENARIOS OF EXPERIMENTS

Parameter	Value
Number of PUs	$2-6$
Field	200×200
SU transmission range (r)	$40\ m$
Node density (ρ)	$2-9$
μ_{on}	0.5 *sec*
μ_{off}	0.5 *sec*
PU MAC	*IEEE 802.11*
PU burst rate	400 *kbps*
SU traffic	40 *kbps*
Number of channels	10
Transceiver energy consumption	$50nJ/bit$
Spectrum sensing consumption	$400nJ$ per slot (δ)
Successful transm. threshold ϵ_z	0.9

V. PERFORMANCE EVALUATION

Here, we present the simulation results for the performance evaluation of the proposed MAC protocol, which is conducted using *ns-2* [30]. The performance metrics for SUs are frame delay, energy consumed per node, and throughput. The impact of SUs spectrum utilization on the PU performance is also observed in terms of PU throughput. The selection of different simulation parameters is summarized in Table II, which are used in different scenarios. SUs share the spectrum of PUs running the IEEE 802.11 MAC protocol and selects one of the channels in the same spectrum dynamically. SUs are deployed in a grid topology, whereas PUs are deployed at the corners of the field appearing on the set of C channels randomly. The performance is compared with the *ad hoc* CR CSA-MAC [4] and also with the fixed spectrum SMAC [20] proposed for WSNs. Simulations are run for at least five times, and the mean values of the performance metric are plotted in the figures. In

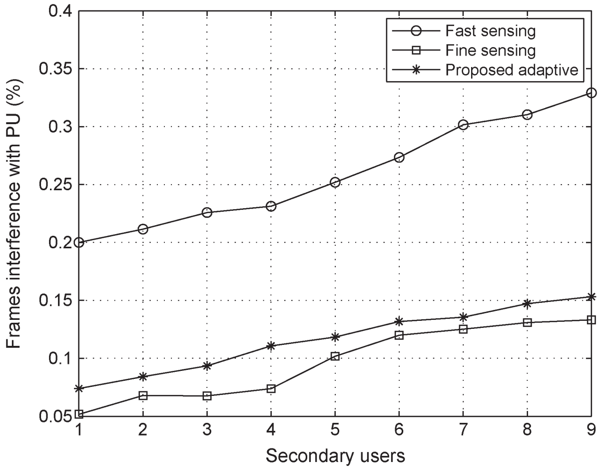

Fig. 4. SU interference with the PUs using different sensing mechanisms.

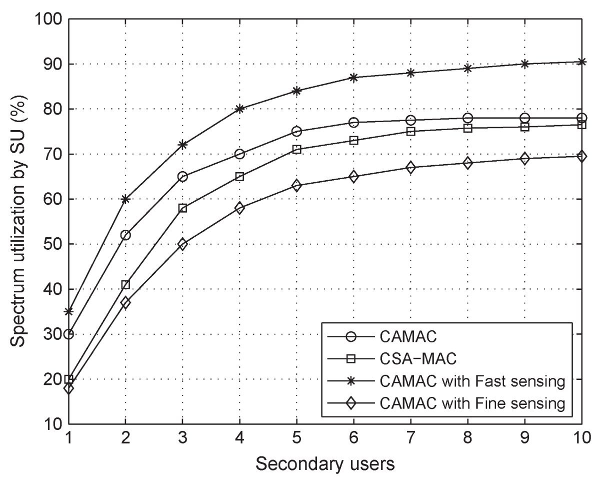

Fig. 5. Spectrum utilization comparison of the proposed CA-MAC with the existing CSA-MAC protocol [4].

the following section, we investigate the impact of PU density, duty cycle, and PU traffic pattern on the performance of SUs.

A. Spectrum Sensing Efficiency

To investigate the efficiency of CAMAC, Fig. 4 shows the SU interference with the PU transmission for fixed sensing periods of fast and fine sensing with the adaptive sensing in CAMAC at varying node density. It is observed that SUs cause high interference with PUs using fast sensing, which is 20% at single SU and increases up to 33% as the SU sources are increased to 9. This is because the fast spectrum sensing results are less reliable. However, the interference with fine sensing remains from 5% to 13% at $z = 30$, which is approximately three times lower than fast sensing on average. Lower interference at fixed fine sensing is achieved at the cost of lower utilization. However, CAMAC also achieves lower interference than fast sensing and up to 15% higher than fine sensing but achieving higher utilization, as shown in Fig. 5. Although the spectrum utilization with fast sensing is higher, it suffers from higher interference that reduces its achievable throughput to much lesser than CAMAC. It can be seen that the utilization of CAMAC is smaller than the existing CSA-MAC [4] initially at about 66% but reduces to 3% as the density of nodes increases. This is due to the fact that CAMAC employs duty cycling that minimizes the chance of finding the receiver as always active and, therefore, suffers spectrum underutilization. However, as the density increases, transmission activity also raises, and the nodes duty cycle ratio is also increased by (12) due to its adaptiveness to transmission activity. Hence, CAMAC achieves higher spectrum utilization closer to the CSA-MAC, although it incorporates duty cycling to conserve energy, which is not implemented in CSA-MAC.

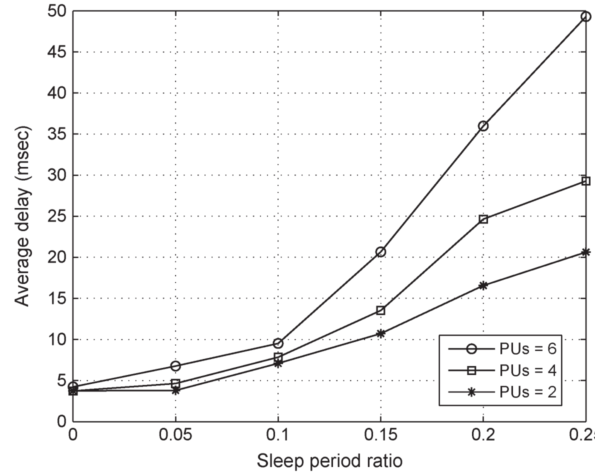

Fig. 6. Average frame delay of SUs at different values of T_s ratio in a duty cycle.

B. Impact of PU Density

In these experiments, ρ is taken as 9, and PUs vary from 2 to 6. Each pair of PUs selects a different channel unlike sharing the same channel, i.e., three pairs use three different channels randomly selected. Fig. 6 reports the average delay of SUs in the presence of three different pairs and varying the sleep period (T_s) of a duty cycle. It is observed that the average delay does not significantly increase at smaller values of T_s at all the three different PU pairs. However, as the value of T_s increases beyond 0.1, the difference due to the number of PUs starts increasing and becomes significantly large at 0.25. The increase of 150% in T_s causes the increase in delay of SU frames by two, three, and five times for two, four, and six PUs, respectively. It is due to the fact that a large number of PUs occupy more number of channels and that the higher sleep period of SUs reduces their opportunity of seeking the FCs. That is, the SU remains in sleep state at a higher value of T_s and does not immediately sense the channel released by the PUs. Thus, the availability of spectrum is minimized at the lower duty cycle (higher value of T_s) in addition to the larger number of PUs that eventually increases the frame delay.

C. Impact of Duty Cycle

Since energy consumption is a major design challenge for a CRSN MAC protocol, the increase in delay due to the lower duty cycle benefits in terms of achieving energy efficiency, as shown in Fig. 7. At the lower value of T_s, SUs remain

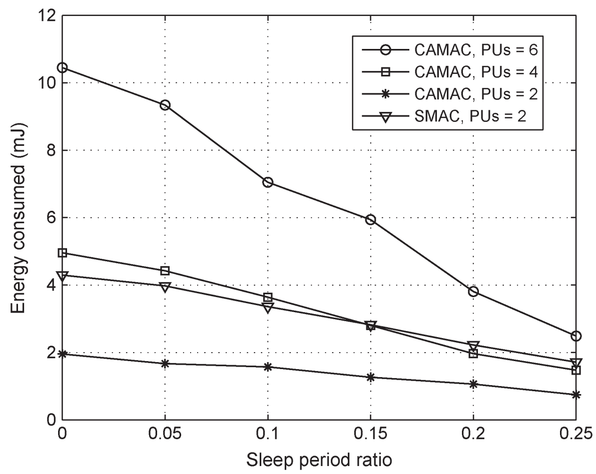

Fig. 7. Average energy consumption per SU at varying sleep period ratio of a duty cycle.

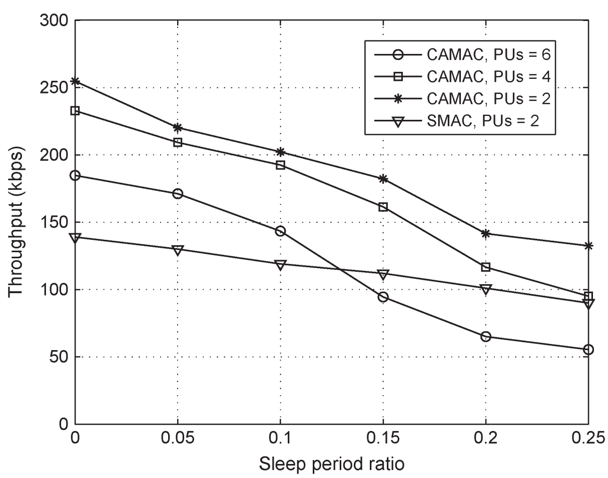

Fig. 8. Average SU throughput at different sleep period ratio of a duty cycle.

awake for a longer period and attempt of DT causes more overhearing of PUs of higher power, as well as SUs transmission apart from the increased transmission failure due to collision. Therefore, the difference in SU energy consumption in CAMAC for three different pairs of PUs is notable until T_s is 0.2. The energy consumption due to PUs increases approximately five times by increasing the PUs from 2 to 6, i.e., three times. On the other hand, the energy efficiency is achieved about five times by reducing the duty cycle up to 25% (at $T_s = 0.25$). Hence, the increase in delay due to reduced duty cycle is compromised in terms of higher energy efficiency. Moreover, the energy consumption in SMAC at $PUs = 2$ is almost twice the CAMAC with two PUs since SMAC does not employ dynamic spectrum access and runs on fixed spectrum that results in excessive waste of energy due to overhearing PU transmission and retransmissions.

Apart from the increased delay at reduced duty cycle, throughput of SUs also decreases, as shown in Fig. 8. Since lower duty cycle minimizes the transmission opportunity of SUs particularly when the number of PUs is higher, throughput of SUs is reduced proportional to the value of T_s. However, the reduction in throughput is not in the order of increased number

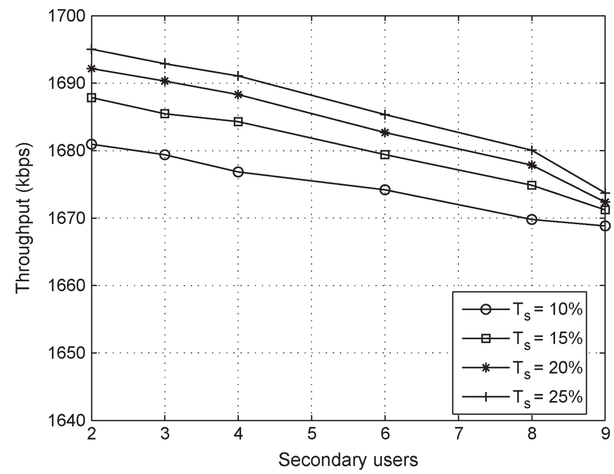

Fig. 9. Throughput of PUs by varying the number of SUs at different values of T_s ratio.

of PUs, which is initially obtained as 185 and 252 Kb/s for two and six PUs, respectively. This is due to the fact that SUs negotiate the channel prior to each transmission, and therefore, they may find the channel available since the traffic pattern of PUs is assumed to be random, as well as when μ_{off} is large. That is, it is quite possible that when a PU transmits on one channel, the other PU is silent, providing an opportunity to SUs on another channel. Eventually, the throughput significantly decreases by increasing the sleep period, which is observed to be approximately half at $T_s = 0.25$, on average, for the three scenarios, although the reduction for six PUs is a little more because the higher sleep time and more PU transmission give a little opportunity to SUs. The throughput is also compared with the SMAC operating on fixed spectrum, and it is clear that it suffers from significantly lower throughput that is about 67% lower than CAMAC at $PUs = 2$ since it cannot evade PU transmission. Hence, the existing MAC protocols proposed for WSNs, no matter how efficiently they perform in WSNs, cannot be applied to CRSN due to their spectrum nonadaptiveness in a CR environment.

Note that there is a crossover between the curves of CAMAC at PUs $= 6$ and SMAC in Fig. 8. It is due to the fact that the throughput in CAMAC decreases with the increase in both PUs and sleep period ratio. By increasing the PUs, the spectrum access opportunity reduces for CAMAC, and therefore, throughput sharply decreases. On the other hand, SMAC operates on a fixed channel, which does not support CR, and there is no restriction on the use of the spectrum. Therefore, the throughput in SMAC decreases only when the sleep period ratio increases. Hence, throughput in CAMAC drops sharply at a higher number of PUs (PUs $= 6$) and sleep period ratio, and it crosses the curve of SMAC that has smaller decay because of only increased sleep period ratio. However, the throughput of CAMAC is still higher than SMAC at a smaller number of PUs.

PUs are the prime users of the spectrum, and it is the fundamental requirement to avoid interruption in PU transmission when SUs access the spectrum dynamically. This feature is evaluated by reporting the aggregate throughput of six PUs by varying the density of SUs interfering their transmission as shown in Fig. 9. It can be seen that the throughput drops

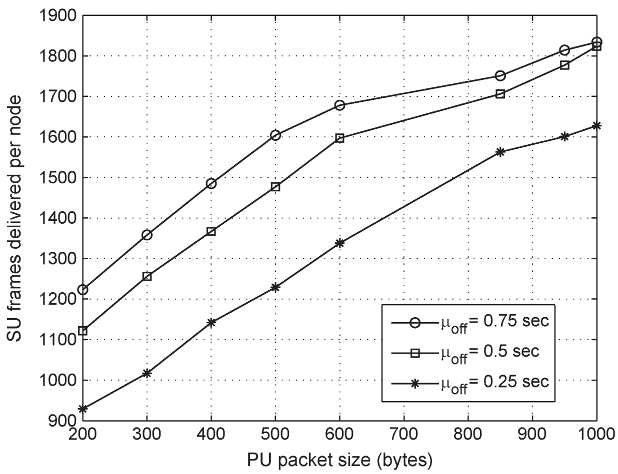

Fig. 10. SU frames per node delivered at different frame sizes of PUs at a fixed traffic rate.

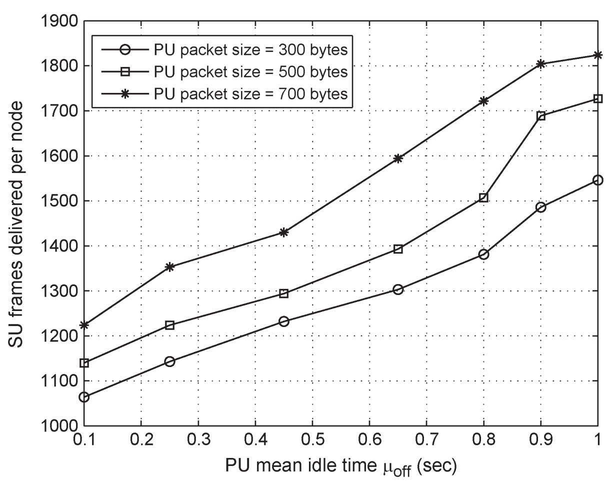

Fig. 11. SU frames per node delivered at different mean idle period μ_{off} of PUs at a fixed traffic rate.

from 1695 to 1675 Kb/s by increasing the SUs from 2 to 9 at sleep period ratio of 0.25, which is not a notable degradation in PU traffic, and thus, the SUs legitimately exploit the available spectrum (see Fig. 9).

D. PU Traffic Impact

Similarly, the impact of the PU traffic pattern on SU transmission is analyzed in two ways: by changing the packet size of PU frames and varying the mean idle period μ_{off} of PUs. Fig. 10 shows the number of SU frames per node delivered by varying frame size of PUs from 200 to 1000 bytes at a fixed μ_{off} set to 0.5 s. The large frame size is observed to be in favor of SU traffic. When the traffic rate of a PU is fixed but the size of the frame is increased, it captures the channel for longer time but at a lesser rate. Intuitively, SUs get wider FC holes that allow them to complete their ongoing transmission successfully, therefore reducing the transmission failures. Moreover, long burst of PU transmission also reduces the false spectrum detection probability, and eventually, SUs successfully detect the channels. By increasing the PU frame size from 200 to 1000 bytes, i.e., five times, the frame delivery is increased up to 60% approximately. Similarly, at a higher value of μ_{off}, the frame delivery is also improved, which is reported to be an increase of 20% by changing μ_{off} from 0.25 to 0.5 s. The relationship of μ_{off} with SU traffic is also analyzed in Fig. 11. It can be seen that the frame delivery is improved by 50% when μ_{off} is increased from 0.1 to 1 s. This increase is further enhanced for a large PU frame size of 700 bytes, which is evident in the results presented in Figs. 10 and 11. Therefore, it can be deduced that the longer idle period of PUs and larger frame size provide better transmission opportunities to Sus, and thus, the spectrum efficiency is increased.

VI. Conclusion

In this paper, CR has been realized for WSNs to benefit the potential advantage of efficient spectrum utilization. This goal is achieved by designing a new state-of-the-art MAC protocol for CRSNs, which incorporates the dynamic spectrum access feature to provide opportunistic transmission while addressing the issue of power limitation of sensor nodes. In particular, we have proposed a CSMA-based on-demand CAMAC protocol for CRSNs that performs spectrum sensing when nodes have data for transmission and runs duty cycling during the idle period to conserve energy. Moreover, it uses an adaptive sensing period that varies between fast sensing and fine sensing, where fine sensing requires a larger sensing period that is computed by characterizing the arrival of PUs and their traffic. The novelty of CAMAC is to limit the number of spectrum sensing nodes by exploiting the spatial correlation of densely deployed sensor nodes and formulating the distortion in correlated spectrum detection probability. Thus, a small number of SR nodes sense the spectrum, and the outcomes of sensing are shared by the nearby nodes for transmission subject to a sensing distortion threshold. Simulation results reveal that CAMAC enables transmission of SUs at a higher rate of up to 250 Kb/s without degrading the throughput of PUs. Moreover, the energy efficiency is achieved at the cost of increased frame delay according to the sleep period ratio of the duty cycle. Hence, it provides an adaptive feature to control delay, energy consumption, and throughput according to the application needs.

References

[1] O. B. Akan, O. B. Karli, and O. Ergul, "Cognitive radio sensor networks," *IEEE Netw.*, vol. 23, no. 4, pp. 34–40, Jul./Aug. 2009.

[2] A. Ghasemi and E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environment," in *Proc. IEEE DySPAN*, Nov. 2005, pp. 131–136.

[3] F. F. Digham, M.-S. Alouini, and M. K. Simon, "On the energy detection of unknown signals over fading channels," *IEEE Trans. Commun.*, vol. 55, no. 1, pp. 21–24, Jan. 2007.

[4] S. Jiang, L.-H. Chao, and H.-L. Chao, "A decentralized MAC protocol for cognitive radio networks," in *Proc. IEEE INFOCOM*, 2011, pp. 24–29.

[5] J. Jia, Q. Zhang, and X. Shen, "HC-MAC: A hardware-constrained cognitive MAC for efficient spectrum management," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 106–117, Jan. 2008.

[6] L. Ma, X. Han, and C.-C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless for wireless Ad Hoc networks," in *Proc. IEEE DySPAN*, Nov. 2005, pp. 203–213.

[7] L. Ma, C.-C. Shen, and B. Ryu, "Single-radio adaptive channel algorithm for spectrum agile wireless Ad Hoc networks," in *Proc. IEEE DySPAN*, Apr. 2007, pp. 547–558.

[8] B. Hamdaoui and K. G. Shin, "OS-MAC: An efficient MAC protocol for spectrum-agile wireless networks," *IEEE Trans. Mobile Comput.*, vol. 7, no. 8, pp. 915–930, Aug. 2008.

[9] S. M. Kamruzzaman, "CR-MAC: A multichannel MAC protocol for cognitive radio Ad Hoc networks," *Int. J. Comput. Netw. Commun.*, vol. 2, no. 5, pp. 1–14, Sep. 2010.

[10] M. Wellens, J. Riihijarvi, and P. Mahonen, "Modelling primary system activity in dynamic spectrum access networks by aggregated on/off-processes," in *Proc. IEEE SECON*, Jun. 2009, pp. 1–6.

[11] L. Tang, Y. Chen, E. L. Hines, and M.-S. Alouini, "Effect of primary user traffic on sensing–throughput tradeoff for cognitive radios," *IEEE Trans. Wireless Commun.*, vol. 10, no. 4, pp. 1063–1068, Apr. 2011.

[12] C. Cordeiro, K. Challapali, D. Birru, and S. Shankar, "IEEE 802.22: The first world-wide wireless standard based on cognitive radios," in *Proc. IEEE DySPAN*, Nov. 2005, pp. 328–337.

[13] H. Zhang, Z. Zhang1, and Y. Chau, "Distributed compressed wideband sensing in cognitive radio sensor networks," in *Proc. IEEE INFOCOM*, 2011, pp. 13–17.

[14] H. N. Pham, Y. Zhang, P. E. Engelstad, T. Skeie, and F. Eliassen, "Optimal cooperative spectrum sensing in cognitive sensor networks," in *Proc. ACM IWCMC*, 2009, pp. 1073–1079.

[15] F. Hu, R. Patibandla, and Y. Xiao, "Spectrum sensing in cognitive radio sensor networks: Towards ultra low overhead, distributed channel findings," *Int. J. Sensor Netw.*, vol. 3, no. 2, pp. 115–122, 2008.

[16] S. Gao, L. Qian, D. R. Vaman, and Q. Qu, "Energy efficient adaptive modulation in wireless cognitive radio sensor networks," in *Proc. IEEE ICC*, 2007, pp. 3980–3986.

[17] A. O. Bicen and O. B. Akan, "Reliability and congestion control in cognitive radio sensor networks," *Ad Hoc Netw.*, vol. 9, no. 7, pp. 1154–1164, 2011.

[18] S. Arkoulis *et al.*, "Cognitive radio-aided wireless sensor networks for emergency response," *Meas. Sci. Technol.*, vol. 21, no. 12, p. 124002, 2010.

[19] Y. Pei, A. T. Hoang, and Y.-C. Liang, "Sensing–throughput tradeoff in cognitive radio networks: How frequently should spectrum sensing be carried out?" in *Proc. IEEE 18th Int. Symp. PIMRC*, Sep. 2007, pp. 1–5.

[20] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *Proc. IEEE INFOCOM*, 2002, pp. 1567–1576.

[21] K. Chowdhury and I. Akyildiz, "OFDM based common control channel design for cognitive radio Ad Hoc networks," *IEEE Trans. Mobile Comput.*, vol. 10, no. 2, pp. 228–238, Feb. 2011.

[22] G. L. Stuber, *Principles of Mobile Communication*. Norwell, MA, USA: Kluwer, 2001.

[23] A. Goldsmith, *Wireless Communications*. New York, NY, USA: Cambridge Univ. Press, 2005.

[24] S. Y. Seidel *et al.*, "Path loss, scattering and multipath delay statistics in four European cities for digital cellular and microcellular radiotelephone," *IEEE Trans. Veh. Technol.*, vol. 40, no. 4, pp. 721–730, Nov. 1991.

[25] A. Rabbachin, T. Q. S. Quek, S. Hyundong, and M. Z. Win, "Cognitive network interference," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 2, pp. 480–493, Feb. 2011.

[26] L. Ma, C.-C. Shen, and B. Ryu, "Single-radio adaptive channel algorithm for spectrum agile wireless Ad Hoc networks," in *Proc. IEEE DySPAN*, 2007, pp. 547–558.

[27] L. Lazos, S. Liu, and M. Krunz, "Mitigating control-channel jamming attacks in multi-channel Ad Hoc networks," in *Proc. ACM WiSec*, 2009, pp. 169–180.

[28] A. O. Bicen, V. C. Gungor, and O. B. Akan, "Spectrum-aware and cognitive sensor networks for smart grid applications," *IEEE Commun. Mag.*, vol. 50, no. 5, pp. 158–165, May 2012.

[29] G. A. Shah, V. C. Gungor, and O. B. Akan, "A cross-layer QoS-aware communication framework in cognitive radio sensor networks for smart grid applications," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1477–1485, Aug. 2013.

[30] ns-2, The Network Simulator. [Online]. Available: http://www.isi.edu/nsnam/ns

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