Energy-Efficient Packet Size Optimization for Cognitive Radio Sensor Networks

Mert Can Oto and Ozgur B. Akan, *Senior Member, IEEE*

***Abstract*—Cognitive Radio (CR) and its dynamic spectrum access capabilities can be exploited by many wireless network architectures including sensor networks. Thus, cognitive radio sensor networks (CRSN) has emerged as a promising solution to address the spectrum-related challenges of wireless sensor networks (WSN). Among others, determination of the optimal packet size is one of the most fundamental problems to be addressed for the practical realization of CRSN. The existing optimal packet size solutions devised for wireless, sensor, and CR networks are not applicable in CRSN regime. Hence, the objective of this paper is to determine the optimal packet size for CRSN that maximizes energy-efficiency while maintaining acceptable interference level for licensed primary users (PU) and achieving reliable event detection at the sink. The energy-efficient optimal packet size is analytically formulated and its variation with respect to different network parameters is observed. Results reveal that PU behavior and channel BER are the most critical parameters in determining the energy-efficient optimal packet size for CRSN.**

***Index Terms*—Cognitive radio sensor networks, optimal packet size, energy-efficiency.**

I. INTRODUCTION

THE main aim of dynamic spectrum access (DSA) is to exploit the instantaneous spectrum availability in order to improve spectrum utilization by opening licensed spectrum to unlicensed users. Cognitive Radio (CR) [5] is introduced as an intelligent wireless communication technology that enables DSA. CR uses its unique capabilities of monitoring spectrum bands and detecting available channels to enable the usage of static allocated spectrum. Furthermore, by dynamically adjusting its operating parameters, it can utilize available channels [1]. These capabilities of CR can be applied to many wireless networks to address unique challenges such as communication over a crowded spectrum, e.g., ISM bands, interference minimization, resilience to jamming.

Motivated by these salient features of CR, in [18], Cognitive Radio Sensor Networks (CRSN) is introduced as a new paradigm to overcome similar challenges observed in traditional sensor networks. CRSN is defined as densely deployed network of sensor nodes that are equipped with cognitive radio transceivers and sensing circuitries and able to observe the event, search available channels and opportunistically communicate with its neighbor nodes in order to reliably deliver the event signal features to a remote sink in an energy-efficient way.

However, inherent energy and hardware limitations of sensor nodes impose challenges for the realization of potential advantages of incorporating CR capability in sensor networks. Furthermore, CRSN nodes must handle additional challenges incurred by CR functionalities such as spectrum sensing, management, and handoff. The existing WSN protocols and designs are not aware of CR functionalities and do not address related challenges. Despite the vast amount of research on WSN, only handful studies on CRSN exist in the literature, which mainly reveal the communication challenges [18], [23], [24], and propose energy-efficient communication techniques [11], [12]. Thus, many open research issues exist for the realization of CRSN.

Among others, determination of the optimal packet size for CRSN is one of the most fundamental problems to be addressed. In fact, short packet size performs better under varying channel conditions and decreases the interference encountered by PU. However, it suffers from the extensive overhead due to header and trailers, and hence, wastes energy. On the other hand, increasing the packet size improves througput and spectrum utilization for unlicensed user with the cost of increasing packet loss probability under the same channel conditions.

There exist several studies on the packet size optimization for wireless networks [2], [3], considering maximization of either energy or throughput efficiency subject to transmit power, data rates, however, without considering CR and dynamic spectrum access. In [7], it is observed that fixed the packet size achieves higher throughput than the exponentially distributed packet sizes in CR networks. However, this work does not consider the inherent challenges and objectives of sensor networks such as energy-efficiency and reliable event detection. In [21], energy-efficient packet size for sensor networks is investigated, which does not address the unique challenges caused by CR functionalities and requirements of DSA. Hence, to the best of our knowledge, the packet size optimization has not been studied for CRSN so far.

Therefore, in this paper, we investigate the energy-efficient packet size optimization problem for CRSN for the first time in literature. Our aim is to determine the optimal packet size for CRSN that maximizes energy-efficiency while maintaining acceptable interference level for licensed users and remaining under maximum allowed distortion level between the tracked event signal and its estimation at the sink node. Since energy-

---

Manuscript received July 25, 2011; revised October 31, 2011; accepted November 23, 2011. The associate editor coordinating the review of this paper and approving it for publication was W. Lou.

The authors are with the Next-Generation and Wireless Communications Laboratory (NWCL), Department of Electrical and Electronics Engineering, Koc University, Istanbul, Turkey (e-mail: akan@ku.edu.tr).

This work was supported in part by the Turkish Scientific and Technical Research Council (TUBITAK) under grant #110E249, and by the Turkish National Academy of Sciences Distinguished Young Scientist Award Program (TUBA-GEBIP).

Digital Object Identifier 10.1109/TWC.2012.021412.021512.111398

efficiency is the most vital consideration of sensor networks, it is chosen as the main optimization objective for the packet size. The usage of fixed packet size is selected due to the inherent energy and hardware limitations of sensor nodes. The main objectives considered when determining the optimal packet size are summarized below:

- *Energy consumption reduction*: Communicating sensor readings in packets with the optimal size that maximizes energy-efficiency in every hop significantly contributes to the energy conservation for entire network, and hence, extends network lifetime.
- *Enhancement of transmission efficiency*: Considering the challenges that are sourced by dynamic spectrum access, energy-efficient packet size design may help decrease the probability of collision between licensed and unlicensed users.
- *Primary user protection*: Our packet size optimization strategy also considers the objective of minimizing potential interference that could be experienced by licensed primary users.
- *Reliable event detection*: Packet size determines the amount of information on the event signal carried in one transmission, and hence, the required transmission rate to maintain acceptable distortion between event signal and its estimation. Thus, the packet size optimization considers the ultimate objective of a sensor network, i.e., realible event detection.

The remainder of the paper is organized as follows. In Section II, the proposed CRSN structure is introduced; the design issues, requirements and assumptions are discussed in detail. Using this model, in Section III, we analytically formulate the energy-efficient packet size optimization problem and derive the stated objectives and constraints. In Section IV, performance analyis is performed and results are discussed. Finally, concluding remarks are given in Section V.

II. CRSN MODEL AND ANALYSIS FRAMEWORK

We consider a cognitive radio sensor network consisting of N nodes and C channels each with bandwidth of B. Licensed and unlicensed users are named as primary user (PU) and secondary user (SU), respectively. CRSN nodes are called SUs. On the other hand, PUs can be any licensed users of the spectrum who have privilege to use the channels. The channels of CRSN are assumed to be avaliable for SUs communication only when they are not used by PUs. Hence, overlay spectrum sharing approach is considered in this model.

Fig. 1 illustrates the general CRSN model to state the energy-efficient packet size optimization problem. In our model, each node is able to observe the event, locally process the observed data, search available channels and by changing its transmission parameters, opportunistically communicate with its neighbor nodes in order to convey data to the sink node. Thus, multi-hop communication is considered.

A. Energy Consumption Analysis of CRSN Node

Energy consumption of a CRSN node before and during the actual transmission need to be examined to formulate the packet size optimization for CRSN. Thus, active mode called cognitive cycle and sleep periods of a CRSN node need to be analyzed in terms of energy consumption.

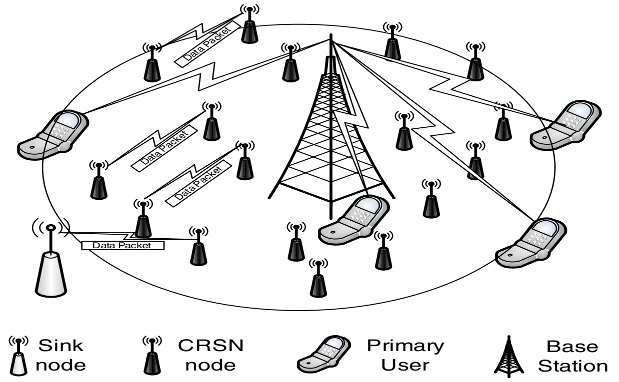


Fig. 1. A general system model for CRSN.

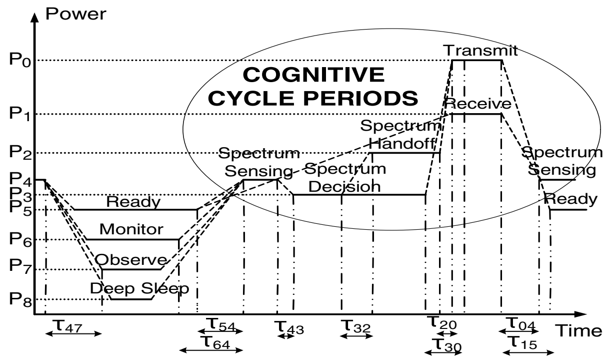


Fig. 2. Sleep and cognitive cycle periods of CRSN node.

Fig. 2 depicts the sleep and the cognitive cycle periods of a CRSN node with respect to their theoretical power levels and time intervals and also transition latencies where P and τ denote power and the transition time, respectively. Additionally, τ_{ij} represents the transition time from period i to period j, e.g., τ_{54} is transition time from ready period to spectrum sensing period.

1) Sleep Periods: When an event occurs in sensor network, CRSN nodes can be at one of the sleep periods below, which are defined based on actual working conditions of the sensor node.

- *Ready Period*: A CRSN node can track the event signal and receive packets from neighbor nodes. However, it cannot process any data because CPU is in idle mode.
- *Monitor Period*: CPU of a CRSN node is in the sleep mode. A CRSN node can detect event signal and receive packets from neighbor nodes in monitor period.
- *Observe Period*: The only active unit is sensing circuitry in observe period. A CRSN node can only detect the event signal.
- *Deep Sleep Period*: The main units of a CRSN node are in the sleep mode. A CRSN node cannot perform any function in deep sleep period.

2) Cognitive Cycle Periods: The transceiver circuitries of CRSN nodes are active in the cognitive cycle periods described below:

- *Sensing Period*: After observation of event, all channels of network are identified as either idle or busy by a CRSN node at sensing period. Then, a CRSN node moves to decision period in order to decide which channel to operate.
- *Decision Period*: If the channel used in previous transmission period, is identified as idle, then a CRSN node decides on this channel and waits for a while in order to provide synchronization with other nodes. Then, it moves directly to transmit period. Otherwise, a CRSN node randomly decides on a channel among the idle ones and moves to handoff period.
- *Handoff Period*: In this period, a CRSN node changes its operating frequency according to decision that is made at decision period. Then, it moves to transmit period.
- *Transmit Period*: A CRSN node transmits its packets to neighbors in this period. Then, if it has more packets to send, it moves to sensing period, otherwise, to one of the sleep periods.
- *Receive Period*: A CRSN node receives data packet from its neighbors at this period. Then, it moves to sensing period in order to route the packet of neighbor nodes.

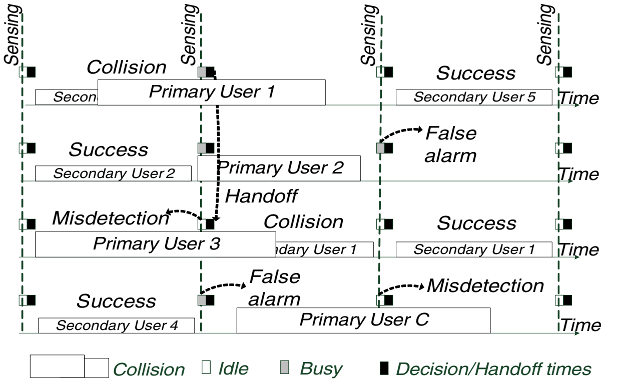


Fig. 3. General Dynamic Spectrum Access Scheme for CRSN.

B. Primary User Behavior Modeling

The PU behavior is assumed to be stationary and ergodic over C number of channels. Without loss of generality for almost all studies of cognitive radio networks, PU traffic can be modeled as an independent and identically distributed ON/OFF process [6], [7], [8], [10]. An ON state defines that channel is used by PUs and an OFF state represents the duration in which channel is unused. Let V_p and L_p be the exponential random variables and describe the idle and busy times of the frequency band, respectively. v_p and l_p denote the means of these exponential random variables. Then, $Pr_{on} = \frac{l_p}{v_p+l_p}$ is the probability of PU channel occupancy and $Pr_{off} = \frac{v_p}{l_p+v_p}$ is the probability of PU absence. Note that Pr_{off} also defines opportunity to access a channel for CRSN nodes.

C. Spectrum Sensing in CRSN

In this work, it is assumed that CRSN nodes may collaboratively perform wideband sensing and have capability to sense all C channels of network using any of the existing main spectrum sensing approaches, e.g., matched filter [14], energy detection [22], [25], and feature detection [4]. However, considering the RF front-end limitations and resource-constrained structure of CRSN nodes, we consider simple energy detection-based spectrum sensing [22], [25] in our model and analysis, as it does not require a priori PU knowledge and excessive computational power despite its high sensitivity to noise variance.

In [8], optimal spectrum sensing method is developed for CR networks. A maximum a-posteriori (MAP)-based energy detection method is proposed based on the PU behaviors. Probability of detection Pr_d and probability of false alarm Pr_f can be expressed as [8]

$$Pr_f(B, t_s, Pr_{off}) = Pr_{off} Q(\frac{\lambda - 2t_s B\sigma_n^2}{\sqrt{4t_s B\sigma_n^4}}) \tag{1}$$

$$Pr_d(B, t_s, Pr_{on}) = Pr_{on} Q(\frac{\lambda - 2t_s B(\sigma_s^2 + \sigma_n^2)}{\sqrt{4t_s B(\sigma_s^4 + \sigma_n^4)}}) \tag{2}$$

where Pr_{on} and Pr_{off} are on and off probabilities, respectively, B is bandwidth of channel, λ is energy detection threshold value, σ_s^2 and σ_n^2 are PU signal and noise variances, respectively, t_s is sensing time. In our work, we use (1) and (2) to determine the detection and false alarm channel state probabilities which will be discussed in Section II-E.

D. Dynamic Spectrum Access for CRSN

Due to the event-driven and application-specific nature of sensor networks, decentralized dynamic spectrum access that enables CRSN nodes to search spectrum holes independently without a central controller stands as a feasible solution. Hence, in our CRSN model, time-slotted decentralized medium access control mechanism is adopted.

In Fig. 3, the channel access scheme of CRSN nodes is presented and the number of channels (C) and the number of PUs in the network are assumed to be 4. Each time slot can be split up to three main sub slots. At the beginning of each time slot, sensing period is reserved for identification of available spectrum bands. With respect to sensing outcome, in the second time period, a CRSN node decides which spectrum band to operate. If the band that is already used by a CRSN node on the previous slot is identified as available channel, a CRSN node does not change its operating frequency and continues its transmission. Otherwise, a CRSN node randomly determines a new frequency band to operate and sets its local oscillators according to new frequency which must be defined as a spectrum hole at spectrum sensing time period. Actual transmission time appears in the last sub time period.

It is assumed that a CRSN node can transmit only one packet in every round. One data packet in one time slot approach ensures low level interference against PU. When SU infers PU activity on channel during sensing period, recognizes that packet sent in the previous slot is corrupted and retransmits it in the next time slot. Whenever a CRSN

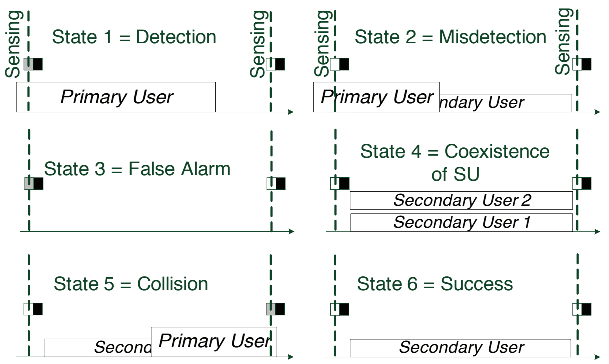


Fig. 4. States of Channel for CRSN under DSA.

node has data packets to send, the six different states may occur on one channel as in Fig. 4:

- *Detection State (State 1)*: A CRSN node senses all channels and infers the presence of PU on the channel used for transmission during the last time slot.
- *Misdetection State (State 2)*: A CRSN node senses a channel and erroneously infers that an actually occupied channel (by PU) is available, which yields high interference for PUs.
- *False Alarm State (State 3)*: A CRSN node senses a channel and incorrectly assumes that it is already owned by PU, although it is available.
- *CRSN Nodes Coexistence State (State 4)*: After the observation of an event, two or more independent CRSN nodes may select the same channel to communicate as a result of decentralized access approach.
- *Collision State (State 5)*: A CRSN node senses all channels of network, identifies one of them as an available band, and starts to communicate. Then, a PU appears and communicates on the same channel during the transmission of CRSN node.
- *Success State (State 6)*: A CRSN node senses all channels, selects one of unoccupied channels, and successfully communicates without any interruption by PU arrival.

E. Channel State Probabilities and BER Analysis

In this part, channel state probabilities, i.e., probability of the channel is in state i as explained above, Pr_i, are defined and analyzed. It is shown in Fig. 4 that detection and misdetection states on the channel can happen only when PU is on the channel. In fact, CRSN nodes either detect or misdetect PU during sensing period when PU actually occupies the channel. Therefore, probability of these two states is equal to the probability that a PU is ON, i.e.,

$$Pr_{on} = Pr_1 + Pr_2 \qquad (3)$$

In contrast, states 3 to 6 can be realized when the channel is idle. Although a CRSN node decides that the channel is in the service of PU, false alarm state occurs when PU is actually not on the channel. Total probability of these four states should be equal to the probability that the PU is in OFF state, i.e.,

$$Pr_{off} = Pr_3 + Pr_4 + Pr_5(l_s) + Pr_6(l_s) \qquad (4)$$

where l_s denotes fixed packet size of a CRSN node. From CRSN point of view, individual channel state probabilities need to be investigated to derive the average BER. Thus, we start with probability of detection state which can be expressed as (2). Then, by subtracting (3) from (2), the probability of misdetection state is calculated as

$$Pr_2(B, t_s, Pr_{on}) = Pr_{on}\left[Q(\frac{2t_sB(\sigma_s^2+\sigma_n^2)-\lambda}{\sqrt{4t_sB(\sigma_s^4+\sigma_n^4)}})\right] \qquad (5)$$

On the other hand, when PU is at OFF state, it is first assumed that probability of false alarm state (Pr_3) is equal to (1). Then, the last three channel states neccessitate a pre-condition that the channel should not be in one of the detection, misdetection and false alarm states.

Assuming that PU behavior is ergodic for every channel of network, the number of available channels for a CRSN node in every decision period can be calculated as CPr_{off}. The probability that CRSN nodes coexist on the same channel is basically the probability that more than one CRSN nodes select the same available channel to operate and can be written as

$$Pr_4 = (Pr_{off} - Pr_3)\left[1 - (\frac{v_p(C-1)-l_p}{Cv_p})^{M-1}\right] \qquad (6)$$

where M is the number of CRSN nodes that observe physical phenomenon.

For much larger PU packet sizes, more than one PU packet cannot be transmitted during CRSN node transmission. Let R denote the data rate of a CRSN node. Since channel idle time is expressed as exponential random variable (V_p), then, the probability of collision in that channel is equal to $Pr(V_p \leq \frac{l_s}{R})$ which can be expressed as

$$Pr(Collision) = 1 - \int_{\frac{l_s}{R}}^{\infty} \frac{1}{v_p} e^{-\frac{t}{v_p}}\,\mathrm{dt} = 1 - e^{-\frac{l_s}{Rv_p}} \qquad (7)$$

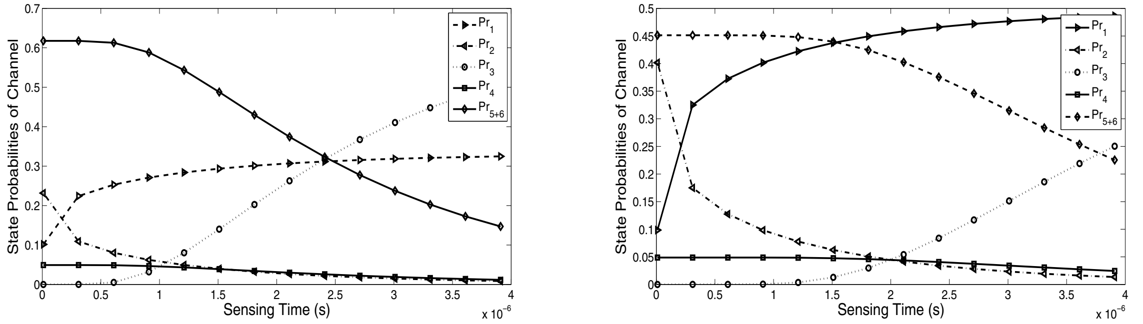
Consequently, the probability of success can be determined as $Pr(Success) = e^{-\frac{l_s}{Rv_p}}$. However, in our network model, the past four channel states must not occur on the channel in order to realize success and collision states. Thus, probabilities of these two states are given as

$$Pr_5(l_s) = (1 - e^{-\frac{l_s}{Rv_p}})(Pr_{off} - Pr_3 - Pr_4) \qquad (8)$$

$$Pr_6(l_s) = e^{-\frac{l_s}{Rv_p}}(Pr_{off} - Pr_3 - Pr_4). \qquad (9)$$

We use different Pr_{on} values in our numerical analysis in order to investigate the effects of primary user behavior. Fig. 5(a) and (b) illustrate the effects of sensing time period on the channel state probabilities under different PU behaviors. Probabilities of succesful and collision states are calculated together because varying sensing time does not affect the probabilities of these two states individually. However, sensing period affects the sum of these channel state probabilities. It can be seen in Fig. 5(a) and (b) that, increasing sensing time reduces the misdetection state probability but increases the probability of false alarm state decreasing the probability of successful transmission.

As there are six different states that a channel can be in during dynamic spectrum access, the average BER, Λ, of a



(a) (b)

Fig. 5. Variation of channel state probabilities with respect to sensing time when (a) $Pr_{on} = \frac{1}{3}$, (b) $Pr_{on} = \frac{1}{2}$.

channel is

$$\Lambda(l_s) = \sum_{i=1}^{6} Pr_i \Lambda_i \tag{10}$$

where Λ_i represents BER of i^{th} state. Clearly, average BER in (10) depends on packet size of SUs as the probability of collision increases with packet size. Note also that BER is zero in detection and false alarm states of channel as nodes actually do not transmit in these states. Hence, normalizing the remaining probabilities yields a more accurate average BER, i.e.,

$$\Lambda(l_s) = \sum_{i=1}^{6} \frac{Pr_i \Lambda_i}{\sum_{j=1}^{6} Pr_j}, \ \ fori, j \neq 1, 3. \tag{11}$$

F. Reliable Event Signal Estimation at Sink in CRSN

In the event area, each CRSN node observes the noisy version of the same event signal which needs to be regenerated at sink node. Hence, it may not be necessary for all CRSN nodes to send their data packets to sink because the data that are contained at packets of CRSN nodes are highly spatially and temporally correlated. Clearly, the packet size determines the event data that is contained in one packet and the number of necessary packets to remain under maximum allowed distortion level between tracked signal and its estimation at sink node.

In [9], distortion metric between actual event signal and its estimation at sink is derived assuming that event signal is a Gaussian random process. The distortion, $D(M)$, is given as [9]

$$\begin{aligned} D(M) \ &= \ \sigma_s^2 - \frac{\sigma_s^4}{M(\sigma_s^2 + \sigma_n^2)}(2\sum_{i=1}^{M} \rho_{(i,s)} - 1) + \\ & \frac{\sigma_s^6}{M^2(\sigma_s^2 + \sigma_n^2)^2} \sum_{i=1}^{M} \sum_{j \neq i}^{M} \rho_{(i,j)} \end{aligned} \tag{12}$$

where M is the number of nodes which sense the event signal and successfully deliver their readings to the sink, σ_s^2 and σ_n^2 are event source signal and noise variances, respectively, $\rho_{(i,j)}$ and $\rho_{(s,i)}$ are the correlation coefficients between nodes n_i and n_j, and the event source signal and node n_i, respectively. It can be seen in (12) that the number of the source nodes plays a crucial role in the determination of distortion level. Therefore, without exceeding the maximum allowed distortion level, the minimum number of source nodes can be given as

$$M^* = \arg\min_{M} \left(D(M) \leq D_{max}\right) \tag{13}$$

where D_{max} is the maximum allowed distortion.

For given D_{max} and signal statistics, M^* could be set with (12) and (13). We consider the tracked event as single point source. Let B_s denote the bandwidth of the source signal, then, a CRSN node sampling frequency should be at least $2B_s$ with respect to Nyquist sampling theorem to recover source signal back at sink. In the observation time (τ_s), sensors take the samples of the event signal. Then, Analog to Digital Converter (ADC) of a CRSN node converts each sample to χ bits. Thus, the optimal packet size should also assure that $K = 2B_s\tau_s\chi$ bits of each of M^* source a CRSN node must reach sink before decision time of sink node (τ_d) ends.

III. ENERGY-EFFICIENT PACKET SIZE OPTIMIZATION FOR CRSN

To formulate the problem of the optimal packet size, following definitions are essential:
Definition 1: k_1 is the total power consumption of transferring one packet to a neighbor node and k_2 denotes the energy consumption of a CRSN node before the actual transmission begins. Therefore, the energy throughput metric, which is denoted as $\eta(l_s)$, can be defined as the ratio of actual one packet transmission energy over total energy spent to transmit/receive a packet and can be expressed as

$$\eta(l_s) = \frac{k_1 l_s}{k_1 l_s + k_2 R} \tag{14}$$

where l_s and R denote fixed packet size and data rate of CRSN node, respectively.
Definition 2: r is the packet reliability metric which describes the probability of receiving all l_s bits information correctly and can be calculated as

$$r(l_s) = [1 - \Lambda(l_s)]^{l_s} \tag{15}$$

Definition 3: $I_p(l_s, l_p)$ is the ratio of average PU interference time over average transmission time of PU. I_{max} is the maximum level of $I_p(l_s, l_p)$ and is set by PU network.
Definition 4: $\tau_g(l_s, M^*)$ denotes the time interval that starts with event occurrence and ends when the last packet, which

is generated by source CRSN nodes (M^*), reaches sink. M^* is the minimum number of required source nodes to remain under the maximum allowed distortion level and is given as (13).

Accordingly, energy-efficient packet size optimization problem can be formulated as

$$\begin{aligned} \underset{l_s}{\text{maximize}} \quad & \eta(l_s)r(l_s) \\ \text{subject to} \quad & I_p(l_s,l_p) \leq I_{max} \\ & \tau_g(l_s,M^*) \leq \tau_d \end{aligned} \tag{16}$$

It is assumed that one bit error causes packet loss, and hence, waste of energy. $k_2 + k_1\frac{l_s}{R}$ is the total expended energy of CRSN nodes to transmit/receive a packet. With respect to reliability metric, either l_s bits of information is received correctly which corresponds to successful transmission and useful energy ($k_1\frac{l_s}{R}$) or a packet is assumed to be corrupted which is the loss of total expended energy ($k_2 + k_1\frac{l_s}{R}$). Hence, energy-efficiency metric is defined in (16) as an objective function that corresponds to the multiplication of energy throughput and reliability metrics. In addition, the l_s value maximizing the objective function is determined as the energy-efficient packet size when it also meets the constraints ($I_p(l_s,l_p) \leq I_{max}$, $\tau_g(l_s,M^*) \leq \tau_d$) of (16).

A. Derivation of Energy Throughput Metric

In [17], [21], it is shown that the required energy to transfer a packet from one CRSN node to other, E_p, is sum of transmitting, E_t, and receiving energy, E_r, i.e.,

$$E_p = E_r + E_t \tag{17}$$

To calculate E_r and E_t, first, energy consumed during each sleep and cognitive cycle periods of CRSN node, which are mentioned in Section II-A, need to be calculated. In Fig. 2, power level and time interval of each period and transition time between periods are depicted. Hence, E_r of a CRSN node can be written as

$$E_r = \frac{P_5 + P_1}{2}\tau_{51} + P_1\frac{l_s}{R} \tag{18}$$

At receiving part, a CRSN node waits in ready period then moves to receive period to collect a packet. At transmitting part, when the event is observed, a CRSN node moves from ready period to sensing period. After identifying available channels, it decides which channel to operate during decision period. At this point, the probability that the channel, which is used during the previous transmission period, is available is Pr_{off}. Therefore, shifting to handoff state can be realized with the ratio of Pr_{on}. According to sensing outcomes, a CRSN node either switches to handoff period or moves directly to transmit period. Hence, energy consumed during transmission is

$$\begin{aligned} E_t(Pr_{off}) \; = \; & P_5(\frac{\tau_{54}}{2}) + P_0(Pr_{off}\frac{\tau_{30}}{2} + Pr_{on}\frac{\tau_{20}}{2}\frac{l_s}{R}) \\ & + P_4E_{t_4} + P_3E_{t_3} + P_2E_{t_2} \end{aligned} \tag{19}$$

where $E_{t_4} = P_4(\frac{\tau_{54}}{2} + \tau_{se} + \frac{\tau_{43}}{2})$, $E_{t_3} = P_3\left[\frac{\tau_{43}}{2} + \tau_{de} + Pr_{on}\frac{\tau_{32}}{2} + Pr_{off}(\frac{\tau_{30}}{2} + \tau_{32} + \tau_{hf})\right]$, $E_{t_2} = P_2(1 - Pr_{off})(\frac{\tau_{32}}{2} + \tau_{hf} + \frac{\tau_{20}}{2})$ denote total energy consumption for sensing, decision, handoff functions, respectively. Therefore, energy consumed during transmission is

$$\begin{aligned} E_t(Pr_{off}) \; = \; & P_5(\frac{\tau_{54}}{2}) + P_0(Pr_{off}\frac{\tau_{30}}{2} + Pr_{on}\frac{\tau_{20}}{2}) \\ & + \sum_{i=2}^{4} E_{ti} + P_0\frac{l_s}{R} \end{aligned} \tag{20}$$

According to (18) and (20), E_p is

$$\begin{aligned} E_p \; = \; & \frac{P_5\tau_{54}}{2} + P_0(Pr_{off}\frac{\tau_{30}}{2} + Pr_{on}\frac{\tau_{20}}{2}) + \\ & \sum_{i=2}^{4} E_{ti} + P_0\frac{l_s}{R} + \frac{P_5 + P_1}{2}\tau_{51} + P_1\frac{l_s}{R} \end{aligned} \tag{21}$$

With respect to (21) and definition 1, k_1 and k_2 parameters in (14) are

$$\begin{aligned} & k_1 = P_0 + P_1 \\ & k_2 = E_5 + \sum_{i=2}^{4} E_{ti} + P_1\frac{\tau_{51}}{2} + P_0(Pr_{off}\frac{\tau_{30}}{2} + Pr_{on}\frac{\tau_{20}}{2}) \end{aligned} \tag{22}$$

where $E_5 = P_5(\tau_{54} + \tau_{51})/2$.

B. Derivation of Packet Reliability Metric

As introduced in definition 2, packet reliability metric is the probability that all bits of one packet are received correctly. Here, we examine (11) and (15) in detail for accurate calculation of packet size optimization problem. $\Lambda(l_s)$ in (11) is calculated based on the average BER of channel states. Therefore, BER of each channel state needs to be computed correctly to obtain an accurate average. In Fig. 4, it is observed that a CRSN node may experience two different types of BER on channel. $\Lambda_S(\gamma_a)$ is BER on the channel when a CRSN node does not encounter any other transmissions on channel where γ_a is signal-to-noise ratio. $\Lambda_I(\gamma_b)$ is BER when a CRSN node encounters another transmission on channel where γ_b is signal-to-noise ratio.

1) BER in channel states: The average BER on four channel states, in which nodes communicate with each other, are derived in terms of $\Lambda_I(\gamma_b)$ and $\Lambda_S(\gamma_a)$ below.

- *BER in Success State (State 6)*: As there is no other simultaneous transmission on the channel, Λ_S is the actual BER for the success state of channel which can be represented as

$$\Lambda_6 = \Lambda_S(\gamma_a) \tag{23}$$

- *BER in Coexistence State (State 4)*: If two or more CRSN nodes transmit simultaneously, a CRSN node experiences interference by another SU during the transmission period. Thus,

$$\Lambda_4 = \Lambda_I(\gamma_b) \tag{24}$$

- *BER in Misdetection State (State 2)*: Nodes certainly experience the PU interference for varying durations. It may either last for the entire transmission period or finish before a CRSN node transmission ends. The probability that PU stops transmission before the end of a CRSN node transmission period can be calculated as

$$1-\int_{\frac{l_s}{R}}^{\infty}\frac{1}{l_p}e^{-\frac{t}{l_p}}\mathrm{dt}=1-e^{-\frac{l_s}{Rl_p}} \tag{25}$$

where l_p is the mean of channel busy time. Thus, the probability that PU transmission continues through entire transmission period is $e^{\frac{-l_s}{Rl_p}}$. When PU leaves the channel before the transmission period of a CRSN node ends, it is shown that the average time that PU stays on the channel, during the transmission period of a CRSN node converges to $Pr_{on}\frac{ls}{R}$ [22]. Hence, the average BER in misdetection state on channel can be calculated as

$$\begin{aligned}\Lambda_2(l_s) \quad = \quad & \Lambda_I(\gamma_b)[Pr_{on}+Pr_{off}e^{\frac{-l_s}{Rl_p}}]+\\ & \Lambda_S(\gamma_a)[Pr_{off}(1-e^{\frac{-l_s}{Rl_p}})]\end{aligned} \tag{26}$$

- *BER in Collision State (State 5)*: As PU channel occupancy duration converges to $Pr_{on}\frac{l_s}{R}$ during the node transmission in misdetection state, BER in collision state is given as

$$\Lambda_5=\Lambda_I(\gamma_b)Pr_{on}+\Lambda_S(\gamma_a)Pr_{off} \tag{27}$$

2) Derivation of Total Average BER: Inserting (23), (24), (26) and (27) into (11), the total average BER experienced by a CRSN node, i.e., $\Lambda(l_s)$, can be expressed as

$$\begin{aligned}\Lambda(l_s,\gamma_a,\gamma_b) \quad = \quad & \Lambda_S(\gamma_a)+c_1[\frac{Pr_2(Pr_{on}+Pr_{off}e^{\frac{-l_s}{Rl_p}})}{Pr_{off}+Pr_2-Pr_3}\\ & +\frac{Pr_4+Pr_{on}Pr_5(l_s)}{Pr_{off}+Pr_2-Pr_3}]\end{aligned} \tag{28}$$

where $c_1=\Lambda_I(\gamma_b)-\Lambda_S(\gamma_a)$. Next, we analyze BER on the channel depending on whether there is any other transmission (Λ_I) or not (Λ_S). The analysis of BER depends on channel model and modulation in use. According to [16], [21], it is reasonable to assume that a CRSN node employs binary orthogonal frequency shift keying (FSK) modulation on a frequency non-selective Rayleigh fading channel. BER for non-fading channel and FSK is expressed as [20]

$$\Lambda(\gamma)=\frac{1}{2}e^{-\gamma/2} \tag{29}$$

Regarding to (29), we must average $\Lambda(l_s,\gamma_a,\gamma_b)$ in (28) over probability density functions of γ_a and γ_b.

$$\Lambda(l_s)=\int_0^{\infty}\int_0^{\infty}\Lambda(l_s,\gamma_a,\gamma_b)p(\gamma_a)p(\gamma_b)\mathrm{d}\gamma_\mathrm{a}\mathrm{d}\gamma_\mathrm{b} \tag{30}$$

where $p(\gamma_a)$ and $p(\gamma_b)$ are the probability density functions of γ_a and γ_b respectively. For Rayleigh fading channel, $p(\gamma_a)$ and $p(\gamma_b)$ follow chi-square distribution and can be given as $p(\gamma_a)=\frac{1}{\overline{\overline{\gamma_a}}}e^{-\gamma_a/\overline{\gamma_a}}$, $p(\gamma_b)=\frac{1}{\overline{\overline{\gamma_b}}}e^{-\gamma_b/\overline{\gamma_b}}$, where $\overline{\gamma_a}$ and $\overline{\gamma_b}$ are average of γ_a and γ_b, respectively. Hence, (30) can be rewritten as

$$\begin{aligned}\Lambda(l_s) \quad = \quad & \int_0^{\infty}\int_0^{\infty}\left[\frac{1}{2}e^{-\gamma_a/2}+(\frac{1}{2}e^{-\gamma_b/2}-\frac{1}{2}e^{-\gamma_a/2})\Upsilon(l_s)\right]\\ & \frac{1}{\overline{\overline{\gamma_a}}}e^{\gamma_a/\overline{\gamma_a}}\frac{1}{\overline{\overline{\gamma_b}}}e^{\gamma_b/\overline{\gamma_b}}\mathrm{d}\gamma_\mathrm{a}\mathrm{d}\gamma_\mathrm{b}\end{aligned} \tag{31}$$

where $\Upsilon(l_s) \quad = \quad [\frac{Pr_2(Pr_{on}+Pr_{off}e^{\frac{-l_s}{Rl_p}})+Pr_4+Pr_{on}Pr_5(l_s)}{Pr_{off}+Pr_2-Pr_3}]$. Therefore, BER of CRSN for FSK modulation on a frequency non-selective Rayleigh fading channel is

$$\Lambda(l_s)=\frac{1}{2+\overline{\gamma_a}}+\Upsilon(l_s)(\frac{\overline{\gamma_a}-\overline{\gamma_b}}{(2+\overline{\gamma_b})(2+\overline{\gamma_a})}) \tag{32}$$

where $\overline{\gamma}=E[\alpha^2]\frac{E_b}{N_o}$ for α represents Rayleigh fading component and follows the Rayleigh distribution and $\frac{E_b}{N_o}$ is the energy per bit over noise power density. Hence, $E[\alpha^2]$ has two degrees of freedom chi-square distribution and its expected value is 2. The differences between γ_a and γ_b arises here as $\frac{E_b}{N_o}$ of γ_b is calculated based on the signal-to-interference and noise ratio (SINR) instead of SNR. γ_a is traditionally computed with SNR. Hence, $\frac{E_b}{N_o}$ of γ_a is expressed as [13],

$$\frac{E_b}{N_o}=\frac{SNR}{R}=\frac{P_{rs}}{N_oR} \tag{33}$$

where N_o is the noise power density and P_{rs} is received power, and $\frac{E_b}{N_o}$ of γ_b is given as [15],

$$\frac{E_b}{N_o}=\frac{SINR}{R}=\frac{P_{rs}}{(N_o+P_{rp})R} \tag{34}$$

where P_{rp} is the received PU power at a CRSN node receiver. To estimate the received power P_{rp}, P_{rs} of transmitters, standard Friis transmission formula is used, i.e.,

$$P_{rs}(d_{ss}) \quad = \quad \frac{P_sG_tG_r\lambda^2}{(4\pi)^2Ld_{ss}^{\delta}10^{(X_\sigma/10)}} \tag{35}$$

$$P_{rp}(d_{sp}) \quad = \quad \frac{P_pG_tG_r\lambda^2}{(4\pi)^2Ld_{sp}^{\delta}10^{(X_\sigma/10)}} \tag{36}$$

where d_{ss} and d_{sp} are distances between two CRSN nodes, and between a CRSN node and PU, respectively, G_t and G_r are antenna gains of receiver and transmitter of CRSN node, λ is the wavelength of the transmit signal. L is the receiver implementation losses. X_σ is the log normal random variable with variance of σ^2 due to shadowing, δ is the path-loss exponent, which typically varies between 2 up to 6 [19].

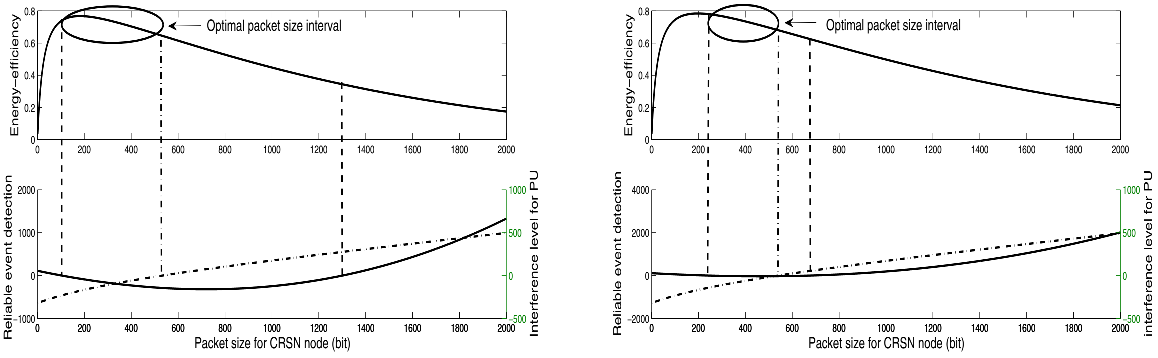
C. Constraint of Acceptable Interference Level for PU

Maintaining acceptable interference for PU is among the fundamental concerns. We define $\kappa(l_s)$ as the average interference time that PU encounters. PU experiences interference in two channel states, i.e., misdetection and collision. Thus, with (26) and (27), $\kappa(l_s)$ is represented as

$$\kappa(l_s)=\frac{l_s\left[Pr_2(Pr_{on}+Pr_{off}e^{\frac{-l_s}{Rl_p}})+Pr_5(l_s)Pr_{on}\right]}{R(Pr_2+Pr_5(l_s))} \tag{37}$$

Recall that the ratio of average interference time over the average transmission time of PU should not exceed I_{max} to remain under maximum allowed interference level. Hence, using (37), constraint ($I_p(l_s,l_p)\leq I_{max}$) in (16) is obtained as

$$l_s[Pr_{on}+\frac{Pr_2Pr_{off}e^{\frac{-l_s}{Rl_p}}}{Pr_2+Pr_5(l_s)}]-I_{max}Rl_p\leq 0 \tag{38}$$



(a)

(b)

Fig. 6. Energy-efficiency of a CRSN node with acceptable interference level and reliable event detection constraints vs CRSN packet size when (a) $\tau_d = 4s$, (b) $\tau_d = 3s$.

D. Constraint of Maximum Distortion Level for Reliable Detection

The total number of the packets required to be delivered to sink within τ_d duration for reliable event detection can be formulated as $\frac{M^*K}{l_s-h}$, where h is the packet header. For the worst case analysis, we assume that a single bit error causes loss of a packet. In the worst case, the number of packets transmitted can be calculated as $M^*K\Lambda(l_s)(\frac{l_s}{l_s-h})$. Thus, the total number of required packets that must reach sink (ψ) is

$$\psi(l_s) = \frac{M^*K}{l_s - h}\left(1 + \Lambda(l_s)l_s\right) \tag{39}$$

Delay bound for a packet to reach the sink is also required for calculating the constraint of $\tau_g(M^*, l_s)$. Let n be the average number of communication hops, n. Then, the total time spent at each hop including transmission can be estimated as $\tau_i = d + \frac{l_s}{R}$, where d denotes average total processing delay at each hop, for $i = 1 \ldots n$. Hence, using (39), we obtain

$$\tau_g(M^*, l_s) = \frac{M^*Kn}{l_s - h}\left[\left(1 + \Lambda(l_s)l_s\right)(d + \frac{l_s}{R})\right] \tag{40}$$

Hence, substituting (40) and defining $c_2 = \tau_d/(nKM^*)$, the last constraint of (16) is restated as

$$l_s^2\Lambda(l_s) + l_s\left(\Lambda(l_s)dR + 1 - c_2R\right) + R(d + c_2h) \leq 0 \tag{41}$$

E. Packet Size Optimization Problem for CRSN

With (22), (28), (38) and (41), and defining $c_0 = k_2/k_1$, energy-efficient packet size optimization problem defined in (16) can be restated as

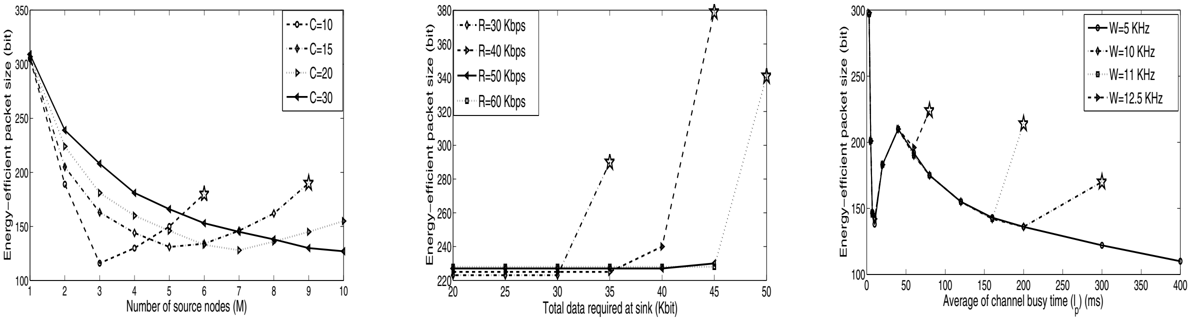
$$\begin{aligned} \underset{l_s}{\text{maximize}} \quad & \frac{l_s}{l_s + c_0R}(1 - \Lambda(l_s))^{l_s} \\ \text{subject to} \quad & l_s[Pr_{on} + \frac{Pr_2 Pr_{off} e^{\frac{-l_s}{Rl_p}}}{Pr_2 + Pr_5(l_s)}] - I_{max}Rl_p \leq 0, \\ & l_s^2\Lambda(l_s) + l_s(\Lambda(l_s)dR + 1 - c_2R) \\ & + R(d + c_2h) \leq 0 \end{aligned} \tag{42}$$

Fig. 6(a) and (b) show energy-efficiency of a CRSN node with varying packet size for $\tau_d = 4$ and 3 seconds, respectively. Constraints in (38) and (41) yield an interval of packet size including optimal that enables to maintain acceptable interference level for PU and reliable event detection. It is observed that when τ_d decreases from 4 sec. to 3 sec., reliable event detection constraint becomes dominant factor to determine energy-efficient optimal packet size. In some cases, energy-efficient optimal packet size cannot satisfy either (38) or (41). As in Fig. 6(b), energy-efficiency of a CRSN node is around 0.8 when $l_s \approx 200$ bits. However, if this packet size is used, the requirement of reliable event detection cannot be satisfied. Note that 200 bits satisfies both constraints in Fig. 6(a).

Optimal packet size problem in (42) can be modeled as a single variable nonlinear constrained optimization problem. Sequential quadratic programming (SQP) is one of the most popular methods to solve these types of optimization problems. Hence, SQP algorithm of MATLAB optimization toolbox is adopted in order to solve energy-efficient packet size optimization problem.

IV. NUMERICAL ANALYSIS OF ENERGY-EFFICIENT OPTIMAL PACKET SIZE

In this section, the variation of optimal packet size with respect to different parameters of CRSN summarized in Table I is observed through numerical analysis. The numerical values in Table I are set according to the previous work on the WSN [13], [15], [17], [21], and CR networks [7], [8], [10]. Note that these values are application-specific parameters and may vary according to demands of applications and constraints of PU protection on different spectrum bands. Additionally, assumptions in this work are made with respect to the previous CR, WSN and CRSN studies to form realistic CRSN architecture. Note that, although changing some assumptions such as sensing method and channel model, to observe the behavior of the optimal packet size under different circumstances slightly affects the numerical results, the critical parameters to determine the optimal packet size stay as the same. For example, considering new detection method for CRSN only changes the channel state probabilities which are confined to PU on and off probabilities. Limiting the channel state probabilities by PU activity restricts sharp variations on the optimal packet size. Therefore, obtained results in this section reveal the general effects of parameters on the optimal packet size in CRSN.



(a) (b) (c)

Fig. 7. Variation of energy-efficient packet size vs. (a) number of source nodes under different number of channels, (b) total data required at sink with different data rates, (c) average of channel busy time with different event signal bandwidth when v_p=80 ms.

TABLE I
OPTIMIZATION PROBLEM PARAMETERS

Symbol	Definition	Quantity
ISM	operating frequency band	2.4 GHz
v_p	average of channel idle time	160 ms
B	channel bandwidth	1 MHz
t_s	sensing time	2 μs
I_{max}	maximum level of interference	0.1
d_{ss}	CRSN nodes distance	8 m
d_{sp}	a CRSN node and PU distance	120 m
N_o	noise power density	$4.14x10^{-21}$
$G_{t/r}$	antenna gains	0 dBi
δ	path-loss exponent	3.5
Pr_{on}	PU occupancy probability	$\frac{1}{3}$
λ	threshold value	5 dB
P_p	PU transmission power	10 dB

A. Effect of Number of Channels and Source Nodes

In Fig. 7(a), the energy-efficient packet size increases with the number of channels due to a decrease in the probability of coexistence on the same channel. On the other hand, an increase in the number of source nodes decreases energy-efficient optimal packet size mainly due to an increase in number of generated packets.

With the increasing the number of source nodes, energy-efficient optimal packet size for $C = 10$ and $C = 15$ decreases sharply down to 100 bits. However, as the number of source nodes keeps increasing, reliable event detection constraint becomes dominant factor and increases the optimal packet size from 100 bits to 200 bits. On the other hand, it can be seen that for $C = 20$, $C = 30$, energy-efficient optimal packet size decreases with increasing number of source nodes. Furthermore, for $C = 10$, $M \geq 7$ and $C = 15$, $M \geq 9$, energy-efficient optimal packet size cannot be calculated due to an increase in BER caused by channel scarcity and also an increase in the total amount of generated data. Note that the points on curves in Fig. 7(a) marked with $\star$ represent the last feasible optimal packet sizes for $C = 10$, $C = 15$.

B. Effect of Total Data Load and Rate

It can be seen in Fig. 7(b) that data rate of a CRSN node determines the maximum total amount of data load that can be transferred to the sink node in a decision time interval. When the total data required at sink node is 25 Kbit, the energy-efficient optimal packet size is approximately 225 bits for all data rates of CRSN nodes. While varying the data from 30 Kbit to 55 Kbit, first, in a sequential manner with respect to data rates, energy-efficient optimal packet size increases from 225 bits up to 400 bits, then, the optimal packet size cannot be determined for these data rates. Note that the points on the curves in Fig. 7(b) marked with $\star$ represent the last feasible solution of energy-efficient packet size optimization problem for $R = 30$, $R = 40$ and $R = 60$.

C. Effect of Event Signal Bandwidth and Channel Busy Time

As shown in Fig. 7(d), when event signal bandwidth becomes higher, it results in a decrease in energy-efficient packet size because estimation of a wideband signal requires more data, and hence, more packets. On the other hand, energy-efficient optimal packet size decreases with increasing the average of channel busy time. However, when $l_p \leq 50$ ms, the requirement of acceptable interference level for PU becomes dominant parameter and reduces the energy-efficient optimal packet size down to 100 bits to reduce the time that PU encounters interference.

For $W = 12.5$ KHz, if the average duration of PU on the channel is around 100 ms, energy-efficient packet size increases due to the requirement of reliable event detection. However, as l_p keeps increasing, energy-efficient optimal packet size cannot be determined for $W = 12.5$ KHz. CRSN cannot convey the total amount of data to the sink node in a decision time interval due to highly occupancy of PU on channels. For $W = 10$ KHz and $W = 11$ KHz, variation of energy-efficient optimal packet size follows the same pattern as $W = 12.5$ KHz with respect to variation of average of channel busy time. Note that the points on the curves in Fig. 7(d) marked with $\star$ represent the last feasible solution of energy-efficient packet size optimization problem for $W = 10$, $W = 11$ and $W = 12.5$.

V. CONCLUSIONS

In this paper, we presented the energy-efficient packet size optimization problem for CRSN considering acceptable interference level for PU and maximum allowed distortion level between event signal and its estimation at sink node. Packet size optimization problem is analytically formulated and SQP method is used to determine energy-efficient optimal packet size. Results reveal that PU behavior and BER are the most critical parameters in determining energy-efficient optimal packet size for CRSN. Variation of these two parameters causes a large variation in energy-efficient optimal packet size between 100 bits to 600 bits. A tradeoff between remaining under the maximum allowed distortion level and the total amount of data load in network is also revealed.

REFERENCES

[1] I. F. Akyildiz, W. Lee, M. C. Vuran, S. Mohanty, "Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey," *Comput. Netw. J.,* vol. 50, no. 13, pp. 2127–2159, Sep. 2006.

[2] P. Letteri and M. B. Srivastava, "Adaptive frame length control for improving wireless link through, range, and energy efficiency," in *Proc. 1998 IEEE INFOCOM*, pp. 564–571.

[3] C. K. Siew and D. J. Goodman, "Packet data transmission over mobile radio channels," *IEEE Trans. Veh. Technol.,* vol. 38, no. 2, 1989.

[4] N. Han, S. H. Shon, J. O. Joo, and J. M. Kim, "Spectrum sensing method for increasing the spectrum efficiency in wireless sensor network," *Ubiquitous Comput. Syst.,* vol. 4239, pp. 478–488, 2006.

[5] J. Mitola, "Cognitive radio: an integrated agent architecture for software defined radio," Ph.D. dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, 2000.

[6] R. Urgaonkar and M. J. Neely, "Opportunistic scheduling with reliability guarantees in cognitive radio network," in *Proc. 2008 IEEE INFOCOM*.

[7] S. Huang, X. Liu, and Z. Ding, "Opportunistic spectrum access in cognitive radio networks," in *Proc. 2008 IEEE INFOCOM*, pp. 1734–1743.

[8] W.-Y. Lee and I. F. Akyildiz, "Optimal spectrum sensing framework for cognitive radio networks," *IEEE Trans. Wireless Commun.,* vol. 7, no. 10, Oct. 2008.

[9] M. C. Vuran, O. B. Akan, and I. F. Akyildiz, "Spatio-temporal correlation: theory and applications for wireless sensor networks," *Comput. Netw. J.*, vol. 45, no. 3, pp. 245–261, 2004.

[10] K. Sriram and W. Whitt, "Characterizing superposition arrival processes in packet multiplexer for voice and data," *IEEE J. Sel. Areas Commun.,* vol. SAC-4, no. 6, pp. 833–846, Sep. 1986.

[11] S. Byun, I. Balasingham, and X. Liang, "Dynamic spectrum allocation in wireless cognitive sensor networks: improving fairness and energy efficiency," in *Proc. 2008 IEEE VTC – Fall*, pp. 1–5.

[12] S. Gao, L. Qian, and D. R. Vaman, "Distributed energy efficient spectrum access in wireless cognitive radio sensor networks," in *Proc. 2008 IEEE WCNC*, pp. 1442–1447.

[13] H. Karl and A. Willig, *Protocols and Architectures for Wireless Sensor Networks*. John Wiley & Sons, 2005.

[14] A. Sahai, N. Hoven, and R. Tandra, "Some fundamental limits in cognitive radio," in *Proc. 2004 Allerton Conf. Commun., Control Comput.*

[15] X. Wang and T. Berger, "Spatial channel reuse in wireless sensor networks," *Wireless Netw.,* vol. 14, pp. 133–146, 2008.

[16] K. Sohrabi, E. Manriquez, and G. Pottie, "Near-ground wideband channel measurements," in *Proc. 1999 IEEE VTC*.

[17] E. Shih, S. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan, "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks," in *Proc. 2001 ACM MobiCom*, pp. 277–286.

[18] O. B. Akan, O. B. Karli, and O. Ergul, "Cognitive radio sensor networks," *IEEE Netw.*, vol. 23, pp. 34–40, July 2009.

[19] T. Rappaport, *Wireless Communications: Principles and Practice*. Printice Hall, 1996.

[20] J. G. Proakis, *Digital Communication*. McGraw-Hill, 1995.

[21] Y. Sankarasubramaniam, I. F. Akyildiz, and S. W. McLaughlin, "Packet size optimization and its implications on error control for sensor networks," in *Proc. 2003 IEEE Workshop Sensor Netw. Protocols Appl.*

[22] H. N. Pham, Y. Zhang, P. E. Engelstad, T. Skeie, and F. Eliassen, "Optimal cooperative spectrum sensing in cognitive sensor networks," in *CMC 2009*.

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

[24] A. O. Bicen, V. C. Gungor, and O. B. Akan, "Delay-sensitive and multimedia communication in cognitive radio sensor networks," to appear in *Ad Hoc Netw. J.*, 2011.

[25] D. Cabric, S. M. Mishra, and R. W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Proc. 2004 IEEE Asilomar Conf. Signals, Syst. Comput.*, pp. 772–776.

Mert Can Oto received the B.S. and M.S. degrees in electrical and electronics engineering from Bilkent University and Middle East Technical University, Ankara, Turkey, in 2007 and 2011, respectively. His current research interests include wireless communications.

Ozgur B. Akan (M'00-SM'07) received the Ph.D. degree in electrical and computer engineering from the Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, in 2004. He is currently Associate Professor with the Department of Electrical and Electronics Engineering, Koc University and the Director of Next-generation and Wireless Communications Laboratory (NWCL). His current research interests are in wireless communications, bio-inspired communications, nano-scale and molecular communications, network information theory.

Dr. Akan is an Associate Editor for IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, *International Journal of Communication Systems* (Wiley), *Nano Communication Networks Journal* (Elsevier), and the *European Transactions on Telecommunications*. He served as an Editor for *ACM Wireless Networks Journal* (2004-2010), *AD HOC Networks Journal* (Elsevier) (2004-2008), as a Guest Editor for several special issues, as the General Co-Chair for ACM MobiCom 2012, General Chair for IEEE MoNaCom 2012, TPC Co-Chair for IEEE ISCC 2012, TPC Co-Chair for the ACM MSWiM 2010, International Vice Chair for IEEE INFOCOM 2006, and in organizing committees and TPC of many conferences. He is an IEEE Communications Society Distinguished Lecturer (2011-2012), IEEE Senior Member (Communications Society), and a member of ACM. He is the Vice President for IEEE Communications Society - Turkey Section. Dr. Akan received the IEEE Communications Society Outstanding Young Researcher Award 2010 for EMEA Region (as runner-up), the IBM SUR Award 2011, the IBM Faculty Award twice in 2010 and 2008, Turkish Academy of Sciences Distinguished Young Scientist Award 2008 (TUBA-GEBIP).