ENERGY-EFFICIENT PACKET SIZE OPTIMIZATION FOR COGNITIVE RADIO SENSOR NETWORKS

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ABSTRACT

ENERGY-EFFICIENT PACKET SIZE OPTIMIZATION FOR COGNITIVE RADIO SENSOR NETWORKS

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Cognitive Radio (CR) has emerged as the key technology to enable dynamic spectrum access. Capabilities of CR can meet the unique requirements of many wireless networks. Hence, Cognitive Radio Sensor Networks (CRSN) is introduced as a promising solution to address the unique challenges of Wireless Sensor Networks (WSN) which have been widely used for reliable event detection for many applications. However, there exist many open research issues for the realization of CRSN. Among others, determination of optimal packet size for CRSN is one of the most fundamental problems to be addressed. The existing optimal packet size solutions devised for CR networks as well as WSN are not applicable in CRSN regime and would cause a waste of energy resources. Hence, the objective of this thesis is to determine the optimal packet size for CRSN that maximizes energy-efficiency while maintaining acceptable interference level for licensed primary users (PU) and remaining under the maximum allowed distortion level between tracked event signal and its estimation at sink. Energy-efficient packet size reduces energy consumption and increases the transmission efficiency for CRSN. In this thesis, the energy-efficient packet size optimization problem is analytically formulated. Then, sequential quadratic programming (SQP) method is used for solving the optimization problem. The variation of optimal packet size with respect to different parameters of CRSN network is observed through numerical analysis. Results reveal that PU behavior and channel bit error rate (BER) are the most critical parameters in determining energy-efficient optimal packet size for CRSN.

Keywords: Cognitive Radio, Sensor Networks, CRSN, Optimal Packet Size

ÖZ

BİLİŞSEL RADYO ALGILAYICI AĞLARDA ENERJİ VERİMLİ PAKET UZUNLUĞU ENİYİLEMESİ

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Bilişsel radyo, dinamik tayf erişimine olanak sağlayan anahtar teknoloji olarak sunulmuştur. Bilişsel Radyo'nun yetenekleri, bir çok kablosuz iletişim ağının kendine özgü gereksinimlerini karşılayabilir. Bundan dolayı, birçok uygulamada olay algılaması için yaygın olarak kullanılan kablosuz algılayıcı ağlarında karşılaşılan benzersiz sorunları çözebilmek için bilişsel radyo algılayıcı ağları (BRAA) ümit vadeden çözüm olarak tanıtılmıştır. Ancak, BRAA'nın gerçekleşebilmesi için bir çok çözülmemiş bilimsel araştırma konusu mevcut bulunmaktadır. Diğerlerinin arasında, en uygun paket uzunluğunun belirlenmesi, BRAA için çözülmesi gereken en temel problemlerden biridir. Bilişsel radyo ve kablosuz algılayıcı ağları için geliştirilmiş en uygun paket uzunluğu çözümleri BRAA için uygulanabilir olmayıp enerji kayıplarına yol açar. Bundan dolayı, bu tezin amacı, BRAA için hem enerji verimliliğini en yükseğe çıkaran hem de ana kullanıcı için makul girişim seviyesini muhaza edebilen ve olay sinyali ile bu sinyalin merkez algılayıcıdaki kestirimi arasındaki bozunumun izin verilen en yüksek bozunum seviyesinin altında kalmasını sağlayan, paket uzunluğunu belirlemektir. Enerji verimli paket uzunluğu, BRAA için enerji tüketimini azaltır ve iletişim verimliliğini artırır. Bu tezde, enerji verimli paket uzunluğu eniyilemesi problemi analitiksel olarak formüle edilmiştir. Eniyileme problemini çözmek için ardışık ikicil dereceden programlama yöntemi kullanılmıştır. BRAA'nın değişik parametreleri için en uygun paket uzunluğunun değişimi numerik analizler yoluyla gözlemlenmiştir. Elde edilen sonuçlara göre BRAA için enerji verimli en uygun paket uzunluğu belirlenmesinde, ana kullanıcı hareketleri ve kanal bit hata oranı en önemli parametrelerdir.

Anahtar Kelimeler: Bilişsel Radyo, Algılayıcı Ağlar, Bilişsel Radyo Algılayıcı Ağları, En Uygun Paket Uzunluğu

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INTRODUCTION

In recent years, production of the wireless devices have tremendously increased due to the overwhelming demand of consumers. Furthermore, in coming years, it is expected that the demand of the operating wireless networks will expand even more massively. The rapid growth of these wireless services reveals the need of effective use of scarce radio spectrum resources. Conventional approach currently used in spectrum allocation is very static and available frequency bands are permanently assigned to the licensed users. Moreover, most of the spectrum is already distributed to the existing licensees. Since radio spectrum is a limited resource and obtaining a new license is very expensive, to find a suitable band to operate for new wireless devices and to update old ones become extremely challenging matters. On the other hand, according to the measurements [24], [25], 60% of spectrum remains unused under 6 GHz. In [26], the spectrum usage between 30 MHz and 3 GHz in New York city in September 2004 is analyzed and the occupancy of the spectrum is estimated as 13%. Hence, extensive measurements indicate that most of the licensed spectrum is unused regardless of location and time. Consequently, the fixed spectrum policy is highly inefficient in terms of spectrum utilization.

To overcome this spectrum utilization problem, Dynamic Spectrum Access (DSA) is proposed as a solution. The main aim of DSA envisioned by DARPA XG program [46] is to exploit the instantaneous spectrum availability by opening licensed spectrum to unlicensed users. DSA allows unlicensed users to monitor the available spectrum resources and communicate opportunistically in a manner that limits the level of interference encountered by licensed user.

Cognitive Radio (CR) is introduced as an intelligent wireless communication technology that enables DSA. In [9], the term "cognitive radio" was first named by Joseph Mitola in 1999. Mitola describes the conceptual overview of CR and defines a new language called the radio knowledge representation language (RKRL) to explain how a CR could address the spectrum utilization problem of personal wireless services. Then, based on the Mitola's visionary study, in [1], Haykin forms a framework for CR including the signal processing and adaptive communication procedures that lie at the heart of CR. In addition to that, in this study, the CR is defined as [1] a radio that has two primary objectives which are efficient utilization of the radio spectrum and highly reliable communications whenever and wherever needed. In order to achieve these objectives, cognitive radio uses its unique capabilities to understand and learn the conditions of its surrounding environment and adapts itself according to information gathered from environment by dynamically adjusting its certain operating parameters e.g., transmit-power, carrier-frequency, and modulation strategy, in real-time.

Under the light of abovementioned definition, it is reasonable to assume that 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 [2]. In addition to improving overall spectrum efficiency, these capabilities of CR can be applied to many wireless networks to address unique communication problems.

1.1 Cognitive Radio Sensor Networks (CRSN)

Wireless sensor networks (WSN) are event-driven systems that are composed of a large number of sensor nodes, which are densely deployed in event area. The main objective of sensor networks is to reliably detect and estimate the source event at the sink from collective information provided by each source node [18]. Despite the fact that the collaborative operation of sensor nodes brings significant advantages over traditional sensing approaches [11], operating in fixed spectrum policy poses unique challenges which can be classified as follows:

- Packet losses and delays due to the scarcity of the available spectrum;

- Excessive power consumption caused by packet losses and retransmission;
- Constant operating parameters, e.g., output power, modulation, under variable channel conditions;
- Inefficient communication performance under the scenarios where multiple overlaid sensor networks coexist;
- Delay of the event detection time at a remote sink node.

In [33], Cognitive Radio Sensor Networks (CRSN) is introduced as a new paradigm to overcome abovementioned challenges of traditional sensor networks and defined as densely deployed network of CRSN nodes which consist of cognitive radio transceivers and sensing circuitries. In fact, the deployment of CR capability in sensor nodes may provide opportunistic channel usage and adaptable operational parameters to address the abovementioned challenges. The realization of these appealing features in CRSN primarily requires efficient spectrum management framework to regulate dynamic spectrum access of densely deployed resource-constrained sensor nodes. To enable DSA, cognitive functionalities can be split up to three main sequential phases which are briefly described below:

1. **Spectrum Sensing**: Spectrum sensing functionality is used to capture the existence of licensed user on spectrum and also provides information about spectrum availability to CRSN nodes. The awareness of spectrum conditions is the most distinctive feature of CRSN nodes in comparison to traditional sensor nodes.
2. **Spectrum Decision**: After analyzing the spectrum sensing results, CRSN node must decide which channel to operate on. Then, the transmission parameters such as transmit power and operating frequency must be adjusted according to decision.
3. **Spectrum Handoff**: When a licensed user starts using a channel that is currently used by CRSN nodes, the licensed user activity must be detected within a certain time through spectrum sensing functionality. Then, CRSN nodes immediately move to another available channel decided by spectrum decision functionality. Thus, this fundamental functionality of cognitive radio is called spectrum handoff.

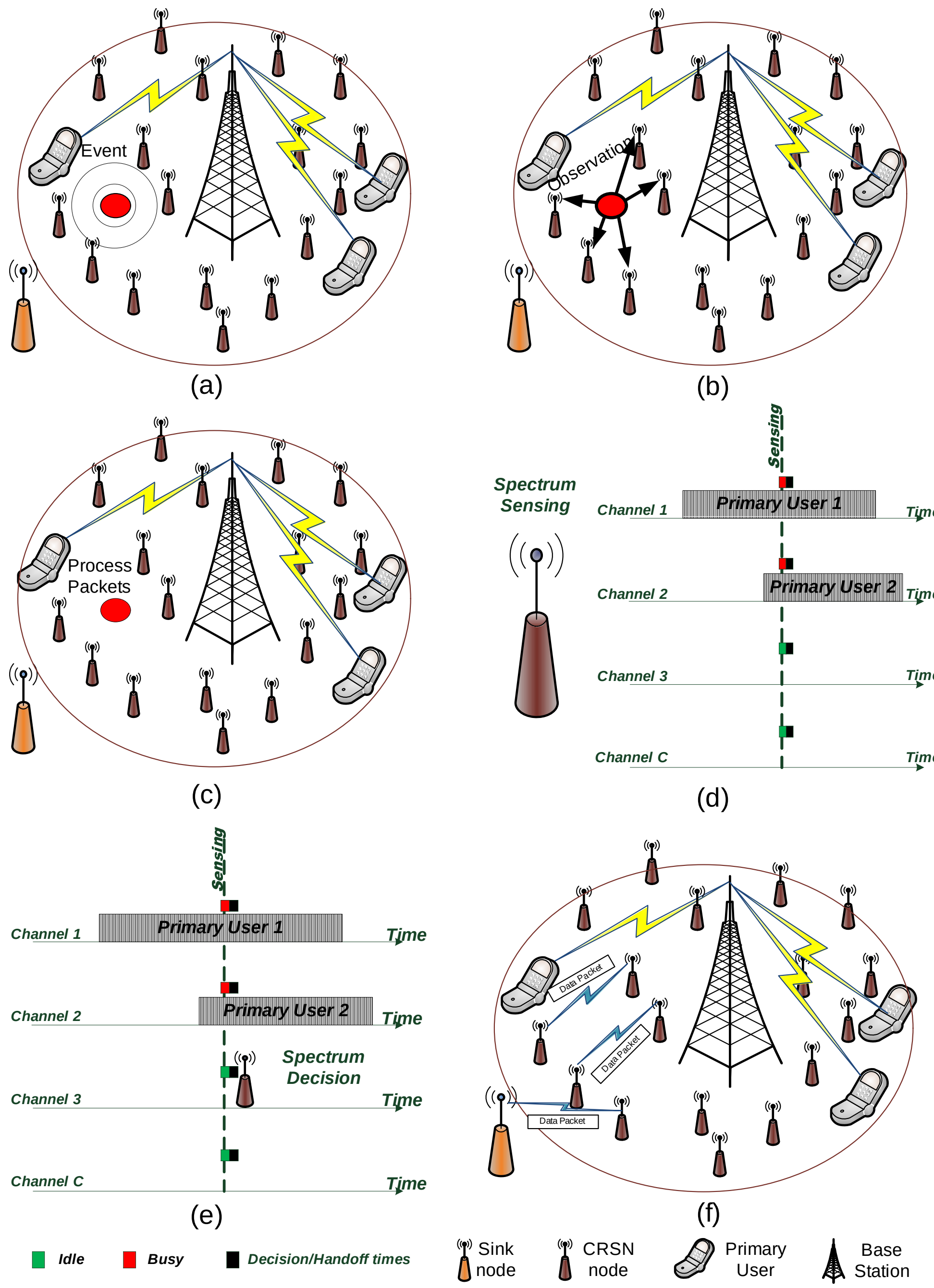

Figure 1.1: Operating scenario of CRSN under primary network (a) event occurrence (b) observation (c) processing (d) spectrum sensing (e) spectrum decision (f) transmission.

With regard to these cognitive functionalities, in CRSN, we assumed that 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. The operating scenario of CRSN is illustrated in Figure 1.1. Despite the fact that novel communication features of CRSN are attractive in the sense of opportunistic spectrum access, inherent energy and hardware limitations of sensor nodes impose challenges for the realization of these appealing features. Additionally, for many sensor network applications, increasing network lifetime is an essential requirement as energy sources of sensor nodes cannot be replenished.

To mitigate inherent energy limitation, several energy-efficient protocols and algorithms [29], [32], [42] for traditional WSN are developed to improve network lifetime. However, CRSN nodes must handle additional challenges which are incurred by CR functionalities. The existing WSN protocols and designs are not aware of CR functionalities and do not address their challenges. Additionally, they consider fixed spectrum band allocation for communication and conventional layered networking approach. In [2], it is pointed out that spectrum sensing, decision and handoff functionalities have direct effects on application, transport, routing, medium access and physical layer functionalities. Therefore, unlike traditional sensor networks, CRSN requires cross-layer design approach. Hence, conventional energy-efficient algorithms and designs of sensor networks are not applicable in CRSN regime and would only cause a waste of energy resources. Thus, cross-layer designs and spectrum aware-communication protocols are needed. We also adopt this approach when we lay out the packet size optimization problem for CRSN in this work.

1.2 The Need for Optimal Packet Size for CRSN

Clearly, the realization of CRSN is based on the development of effective, energy-efficient algorithms and designs. However, there exist many open research issues for the realization of CRSN. Among the others, determination of optimal packet size for CRSN is one of the most fundamental problems to be addressed. A packet is basically defined as the smallest communication entity in a network. All the communication between sensor nodes over an entire CRSN, and detection/estimation of event signal at remote sink node are realized by conveying packets carrying samples of the event signal from one node to other. The existing optimal packet size solutions devised for CR networks as well as WSN are not applicable in CRSN.

Therefore, the need for optimal packet size for CRSN that handles the challenges of both CR and WSN, steps forward among the many other required energy-efficient algorithms and designs. Despite the fact that energy-efficient packet size for traditional WSN is investigated in [39], challenges imposed by CR functionalities are not addressed in that work.

The tradeoff between short packet size and long packet size for CRSN can be explained as follows:

- Short packet size performs better under the varying channel conditions and decreases the encountered interference caused by DSA against licensed user. However, it suffers from the extensive overhead due to header and trailers, and energy consumption of the processes which occur before the actual packet transmission.
- Long packet size meets requirement of massive data transmission in short time for accuracy of detection at sink and increases the spectrum utilization for unlicensed user. On the other hand, as the packet size increases, the probabilities of packet loses due to bit errors and collision with licensed user increase as well.

Our aim in this work is to determine 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 signal and its estimation at remote sink node. Since energy-efficiency is the most vital consideration of sensor networks, it is chosen as the main optimization objective for packet size. The usage of fixed packet size is selected due to the inherent energy and hardware limitations of sensor nodes.

The major objectives considered when determining optimal packet size for CRSN are summarized as follows;

- ***Energy consumption reduction***: Event-driven communication nature of CRSN may yield bursty traffic related to the application-specific requirements and event signal characteristics. Basically, observed data packets from source CRSN nodes need to be immediately sent to the sink node through CRSN. Communicating with packet size that maximizes energy-efficiency in every hop significantly contributes to the energy conservation for entire CRSN, and hence, extends network lifetime of CRSN.

- ***Enhancement of transmission efficiency***: Considering the challenges that are sourced by dynamic spectrum access, in energy-efficient packet size design decreases the probability of collision between licensed and unlicensed users and eliminates the packet losses due to concurrent transmission. When a packet is corrupted due to concurrent transmission, it corresponds to total waste of energy that is consumed for transmitting and receiving a packet. Hence, determination of optimal packet size that concerns both requirements of CR and sensor networks, reduces packet losses and leads to enhancement of transmission efficiency and also energy-efficiency.

- ***Primary user protection***: In addition to maximizing energy-efficiency, our packet size optimization strategy also considers the objective of minimizing potential interference that would be experienced by licensed primary users. In CRSN, communicating with larger packet size increases the probability of collision between CRSN node and licensed primary user. Consequently, the time that PU encounters interference on the channel increases. Considering the time that PU encounters interference on channel, in the design of the optimal packet size for CRSN protects PU from the disruptive communication of CRSN nodes and helps to reduce the interference that may occur during DSA.

- ***Maintaining reliable event detection***: The main aim of densely deployed CRSN nodes is to reliably detect and estimate the source event at the sink from collective information provided by each source node while maintaining acceptable interference level for licensed primary users [18]. Each source CRSN node generates its data packets and sends them to the sink. Packet size determines the amount of the event data that is contained in one transmission unit, i.e., packet and hence, the number of necessary packets to be delivered to remain under the maximum allowed level of distortion between tracked event signal and its estimation at the sink node. Therefore, the collective information provided by each source node at the sink are highly dependent on packet size and number of packets. As a result, energy-efficient packet size that is determined by concerning these abovementioned parameters provides significant improvement for detection of event reliability at sink.

- ***Realization of collaborative approaches for CRSN***: In [43], [44], [45], collective approaches of the spectrum sensing methods are studied for CRSN. In these works, it is assumed that nodes are aware of the network conditions by exchanging information among themselves. However, packet transfering of neighbor CRSN nodes is not investigated in detail. Hence, determining optimal packet size for CRSN helps evaluate the costs of these collaborative approaches for CRSN more precisely and examine the suitability of these approaches for the realization of CRSN.

Considering the need for a packet size and its objectives for CRSN, we emphasize that determining energy-efficient optimal packet size that is designed to address both requirements of CR and sensor network brings significant enhancement to realization of CRSN.

1.3 Organization of Thesis

The remainder of the thesis is organized as follows. In Section 2, we overview the existing related work on CRSN and packet size optimization in wireless networks. In Section 3, the proposed CRSN structure is introduced and the design issues, requirements and assumptions are discussed in detail with respect to the existing studies on both sensor and CR networks. Under this model, in Section 4, we analytically formulate the energy-efficient packet size optimization problem and examine the major optimization methods in order to solve the problem. Then, in Section 5, numerical results and simulations are performed and results are discussed. Finally, concluding remarks are given in Section 6.

CHAPTER 2

RELATED WORK

In this chapter, we overview the existing related work. We first explore the existing packet size optimization studies in the literature. Then, we capture the current state-of-the-art in communication techniques for CRSN.

2.1 Packet Size Optimization in Sensor and Ad Hoc Networks

In the literature, there exist several studies on packet size optimization for wireless networks [5], [7], [13]. In these studies, packet size optimization focuses on the maximization of either energy or throughput efficiency subject to many unique communication parameters such as transmit power, data rates.

In [7], the effect of Rayleigh fading over packet sizes in radio mobile channels is analyzed. In the analysis, fade and interfade channel states are defined according to the fade margin value. Then, the packet is assumed to be corrupted when the channel is in the fade state. According to this assumption, the effects of the fade margin, mobility and data rate on packet size are explored. Obtained results in this study show that data rate and fade margin are the critical parameters in terms of packet loss probability for Rayleigh fading channels.

In [5], adaptive frame length notion is introduced in wireless links in order to combat against variable channel conditions in terms of throughput, transmission range and output power. Theoretical and experimental analysis are investigated by using WaveLAN radio in this work. However, authors underline that the estimation of channel conditions in order to vary frame length and situation of the frames that are already sized and forwarded to lower layers are the open issues to be addressed for the realization of adaptive frame length in wireless links. Furthermore, considering processing, memory and transceiver limitations of low-end sensor nodes, adaptive frame length does not stand as a promising solution in CRSN.

On the other hand, in [13], exponentially distributed and fixed packet sizes are compared in the sense of throughput performance for CR networks. In the analysis, it is clearly observed that fixed packet size achieves higher performance than the exponentially distributed packet sizes. Additionally, while considering the probability of collision and the time that PUs and SUs coexist on the channel, it is observed that smaller packet size performs better in comparison to large packet size. However, spectrum sensing is assumed to be perfect and the results of imperfect sensing are ignored in this work.

In [39], energy-efficient packet size for sensor networks is investigated. Even though this work sheds light on our research, it does not address the unique challenges caused by CR functionalities and requirements of DSA.

Although packet size optimization is very important as clearly shown by these studies, to best of our knowledge, it has not been studied for CRSN so far.

2.2 Cognitive Radio Sensor Networks

Despite the considerable amount of research on wireless sensor networks (WSN) [3], [4], [6], only handful studies on CRSN can be found in the literature. First, in [33], CRSN paradigm has been introduced to the literature and it has been clearly underlined that additional CR capabilities incorporated to wireless sensor networks can address the unique requirements of densely deployed sensor nodes. Then, the suitability of the existing network solutions for both CR and sensor network in CRSN are discussed in terms of their advantages, limitations and shortcomings along with the open research challenges.

In [19], an adaptive multi-carrier modulation strategy is introduced which aims to maximize the network lifetime by selecting the optimal constellation size for CRSN. In addition to that, matched filter detection is proposed based on the pilot tone detection for sensing method. The pilot is assumed to be a sinusoidal signal periodically transmitted on a subcarrier.

In [20], it is proposed that all the cognitive functionalities are to be managed by the dedicated coordinator in order to achieve spectrum utilization as fair as possible by using Modified Game Theory (MGT) in WSN. However, proposed network is designed in a hierarchical manner where some emergency sensor nodes among others, have priority for capturing channels and obtaining required data rates.

In [21], authors work on the optimization problem that minimizes energy consumption per bit over all channels of network with constrains of required data rate and output power bound. In this study, it is assumed that CRSN nodes can select multiple channels to transmit for obtaining required data rate. However, adaptive channel spacing and distributed power control algorithms costs computational complexity and energy expenditure.

In [47], the main design challenges and principles for reliability and congestion control in CRSN are introduced. Several existing transport protocols and algorithms separately devised for cognitive radio, ad hoc networks as well as WSN are analyzed according to their suitability for CRSN. Results reveal that the existing solutions are not applicable to CRSN regime. Thus, it is pointed out that a novel reliability and congestion control mechanism for CRSN is an urgent need.

In [48], authors explore the main design challenges and principles for multimedia and delay-sensitive data transport in CRSN. Specifically, the challenges for real-time transport in CRSN are examined in different spectrum environments of smart grid, e.g., 500kV substation, main power room and underground network transformer vaults. It is emphasized that communication impairments due to spectrum sensing and mobility, such as excessive delays and packet losses incurred by cognitive cycle must be considered in the design of CRSN transport protocols.

Under the lights of abovementioned studies, it can be highlighted that packet size optimization in CRSN that brings significant improvements for the realization of CRSN is yet to be investigated. Therefore, in this thesis, we will investigate the energy-efficient packet size optimization problem for CRSN for the first time in literature.

CHAPTER 3

CRSN MODEL and ANALYSIS FRAMEWORK

We consider a cognitive radio sensor network consisting of N CRSN 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. In our model, PUs do not change their traffic patterns, activities and transmission parameters according to SUs. Furthermore, PUs have the privilege to access their own channels and communicate when they desire. On the other hand, SU can communicate over these channels only when PU have no data to transmit.

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 used for our CRSN model. The idle time of network channels is called "spectrum holes" or "white space" which enables CRSN nodes to opportunistically access channels to send data packets.

3.1 Energy Consumption Analysis of CRSN Node

Energy-efficient packet size optimization for CRSN clearly indicates the examination of energy consumption of CRSN node during actual transmission and also before actual transmission begins. Therefore, active mode called cognitive cycle and sleep periods of CRSN node need to be analyzed in terms of energy consumption. To address this, first, we explore the main units of CRSN node architecture and their objectives. Then, we introduce sleep periods and cognitive cycle of CRSN node concerning the cognitive functionalities originated by DSA which are mentioned in Section 1.1. Afterwards, the mode of major units of CRSN node are examined according to cognitive cycle and sleep periods.

3.1.1 Architecture of CRSN Node

CRSN node is a typical sensor node that has capability to enable cognitive functions. In [33], the hardware structure of CRSN node is illustrated as shown in Figure 3.1. With the aid of this study, it is reasonable to assume that one CRSN node is composed of five main units. We classify these main units and discussed their objectives below,

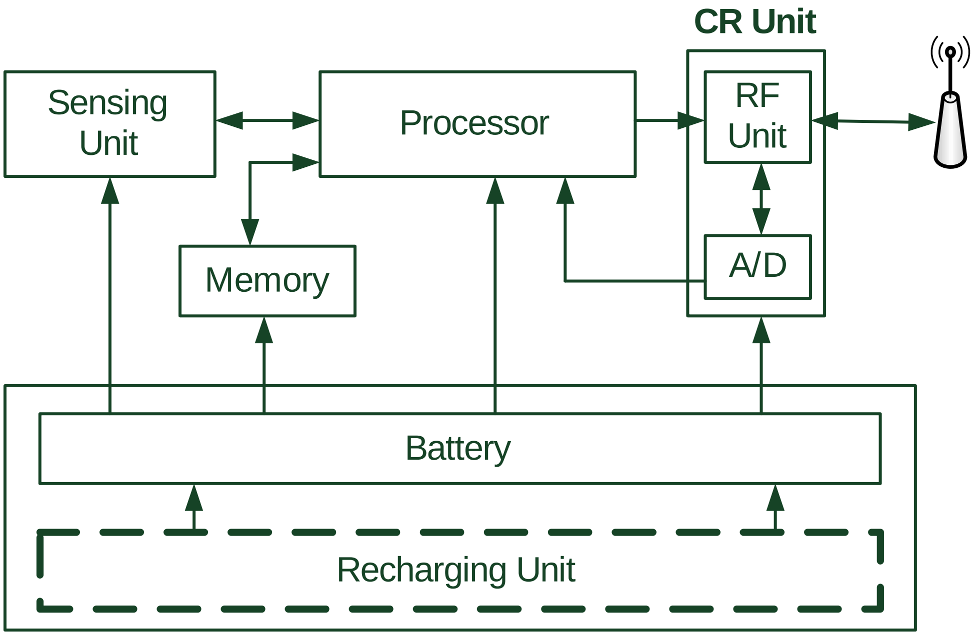

Figure 3.1: Architecture of a CRSN node.

1. Central Processing Unit (CPU): CPU is the executive controller of CRSN node. The tasks of this core part are to collect data from sensor side, process and decide where to send it. Then, according to spectrum sensing readings, it identifies available channels and selects a channel to communicate. Furthermore, CPU is also responsible for routing of the received packets from neighbor nodes.

2. Random Access Memory: The duty of this unit is the storage of sensor readings and data packets of other nodes.

3. Transceiver: This entity is composed of transmitter and receiver. Most of the functional differences between traditional sensor node and CRSN node appear at transceiver unit. In a traditional sensor node, receiver converts incoming radio waves to a bit stream and forwards them to CPU. Conversely, transmitter transforms bit streaming forwarded by CPU to radio waves. However, in CRSN node, in addition to these traditional transceiver duties, this unit is also responsible for the efficient spectrum management in order to realize dynamic spectrum access. Thus, transceiver of CRSN node enables to perform the cognitive functions such as spectrum sensing, decision and handoff.

4. Sensor: Sensor unit is in the charge of event signal detection and sensing.

5. Power Supply: The power supply of CRSN node has a paramount importance among the other CRSN node units because it has a significant influence on network lifetimes. Batteries are the typical power source for sensor nodes.

3.1.2 Cognitive Cycle and Sleep Periods of CRSN Node

For our network model, Figure 3.2 depicts the sleep and the cognitive cycle periods of 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.

3.1.2.1 Sleep Periods

When an event occurs in sensor network, CRSN nodes can be at one of the deep sleep, observe, monitor and ready sleep periods. These sleep periods are defined based on actual working conditions of the sensor node and are briefly explained below.

- *Ready Period*: CRSN node can track the event signal and receive packets from neighbor nodes in ready period. However, it cannot process any data because CPU is not in active mode.

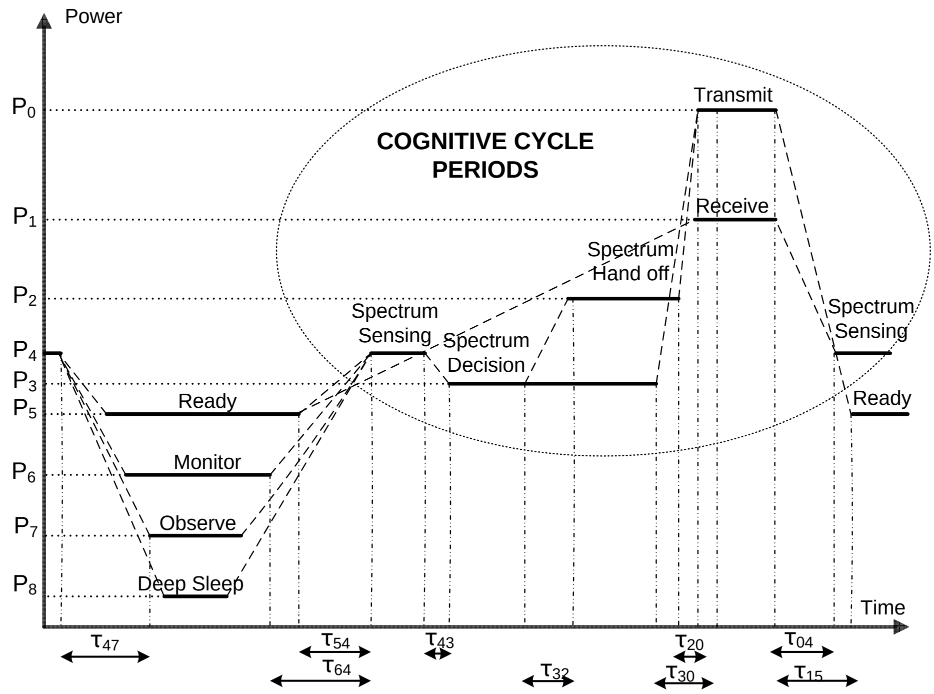

Figure 3.2: Sleep and cognitive cycle periods of CRSN node.

- *Monitor Period*: CPU of CRSN node is in sleep mode. 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. CRSN node can only detect the event signal.

- *Deep Sleep Period*: The main units of CRSN node are in sleep mode. CRSN node cannot perform any function in deep sleep period.

The main aim of defining these sleep periods is to reduce energy consumption at inactive times of sensor nodes [32]. When CRSN nodes stay down to deeper sleep periods, transition overhead in terms of time increases. Therefore, the sleep periods of CRSN node are set according to application-specific requirements and event signal characteristics.

3.1.2.2 Cognitive Cycle Periods

- *Sensing Period*: After observation of event, all channels of network are identified as either idle or busy by CRSN node using one of the spectrum sensing methods as will be discussed in Section 3.3 at sensing period. Then, CRSN node moves to decision period in order to decide which channel to operate.

- *Decision Period*: If the channel that is used in the previous transmission period, is identified as idle, then CRSN node decide on this channel and waits for a while in order to provide synchronization with other CRSN nodes. Then, it moves directly to transmit period. Otherwise, when the previous operating channel is remarked busy, CRSN node randomly decides on a channel among the ones identified as idle. Afterwards, it moves to handoff period.

- *Handoff Period*: In this period, CRSN node changes its operating frequency according to decision that is made at decision period. Then, it moves to transmit period.

- *Transmit Period*: CRSN node transmits its data packets to neighbor CRSN nodes at this period. Then, if it has more packets to send, it moves to sensing period. Otherwise, it moves to one of the sleep periods.

- *Receive Period*: CRSN node receives data packet from its neighbor CRSN nodes at this period. After receiving data packet, it moves to sensing period in order to route the packet of neighbor CRSN node.

3.1.3 Power Modes under Cognitive Cycle and Sleep Periods

The power mode of CRSN node units at cognitive cycle and sleep periods correspond to various levels of energy consumption at these periods. To analyze energy consumption of CRSN node for determination of energy-efficient optimal packet size, we investigate in detail power modes of sensor nodes with respect to sleep periods and cognitive cycle periods summarized in Table 3.1.

Table 3.1: Component Power Modes for CRSN node

Period	***CPU***	***Sensor***	***Transceiver***
Transmit	active	sense	tx
Receive	active	sense	rx
Handoff	active	sense	tx/rx
Decision	active	sense	rx
Sensing	active	sense	rx
Ready	idle	sense	rx
Monitor	sleep	sense	rx
Observe	sleep	sense	off
Deep Sleep	sleep	off	off

3.2 Primary User Behavior Modeling

The traffic statistics of PU play a crucial role for determination of energy-efficient packet size for CRSN because it might not be possible to determine packet size for SU when the channel is extensively used by PU. The PU behavior is assumed to be stationary and ergodic over C number of channels. The aggressiveness of PU constrains the opportunistic spectrum holes for CRSN node. Hence, the existence of optimal packet size for SU is closely dependent on the PU activity. 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. An ON state defines that channel is used by PUs and an OFF state represents the duration in which channel is unused.

In [10], it is mentioned that the user activities in many examples of real networks such as Wi-Fi, cellular and wireless mesh networks can be modeled by these processes. In [13], the PU arrival process is Poisson while the ON time distribution can be general. It is explained that these assumptions fit in many situations such as data network and call arrival process for voice traffic. In [15] and [17], PU activity, both ON and OFF time distributions are modeled as exponential distributions. Morover, in [43], PU traffic pattern is assumed to be two-state independent and identically distributed ON/OFF process. Both busy and idle time distributions are exponential for CRSN.

Under the lights of all above studies, PU behavior is modeled as ON/OFF process in our CRSN model. V_p and L_p are the exponential random variables and describe the idle and busy times of the frequency band. v_p and l_p denotes the means of these exponential random variables. Consequently, $Pr_{on} = \frac{l_p}{v_p+l_p}$ 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 node.

3.3 Spectrum Sensing in CRSN

In CRSN architecture, spectrum sensing is the core of the overall cognitive cycle and general process to capture the existence of licensed user on the band. In [15], two different types of sensing strategies are exploited in order to realize multiple spectrum sensing, i.e., wideband sensing and sequential sensing. In wideband sensing, transceiver can sense multiple spectrum bands over a wide frequency range at a time. Furthermore, in [49], the conceptual architecture of a wideband front-end for cognitive radio is illustrated. It is underlined that the realization of this architecture requires specifically wideband amplification, mixing and analog-to-digital conversion of over a GHz or more of bandwidth. In our work, it is assumed that CRSN nodes perform wideband sensing and have capability to sense all C channels of network. However, this is a very challenging task due to the RF front-end limitations and resource-constrained structure of CRSN node. In [12], algorithm of sensing subset of channels is proposed instead of sensing all channels. However, selection criteria of channels to form a subset for sensing is not addressed. Therefore, despite the fact that sensing all C channels stands as an energy-inefficient approach, it is mandatory to enable DSA without a central coordinator. Furthermore, accurate detection of licensed user on the band assures undisturbed licensed user communication and avoids the collision between primary and secondary users which yields to reduce data packet losses due to simultaneous transmissions. Since energy-efficiency is the primary concern of sensor nodes, avoiding packets losses makes significant improvement on energy savings. Hence, although additional energy consumption is required for sensing all C channels, it is necessary for identifying spectrum holes and indicating the existence of PU in channels.

In our CRSN model, decentralized network architecture model is preferred considering the dense deployment nature of sensor networks. There is no such central entity that searches all spectrum band and sends all available spectrum holes information to members of CRSN. Thus, every single CRSN node should sense all channels when it has data to transmit. Cooperative sensing methods have better performance than individual sensing under the low signal-to-noise ratio (SNR) regime and also solve the hidden terminal problem [15]. However, individual sensing methods are much more realistic because assuming that CRSN nodes share their sensing information via sending data packets before the optimal packet size determination is a self-contradicting phenomenon. Thus, the distributed and cooperative spectrum sensing in CRSN and also synchronization between CRSN nodes are beyond the scope of this thesis.

3.3.1 Applicability of Existing Spectrum Sensing Approaches

Sensing is one of the most distinctive capabilities of CRSN node compared to traditional sensor node. In the literature, various spectrum sensing approaches are presented. In this part, we discuss the existing spectrum sensing approaches from the perspective of their applicability to CRSN.

One of the most common approaches in the existing studies is matched filter detection method. In [28], it is shown that under Gaussian noise, the performance of matched filter detection method is optimal. Furthermore, for a known signal, this method maximizes SNR that leads to the best detection results. However, the requirements of matched filter detection method do not suit well on energy limited structure of CRSN node. First, computational and hardware costs of matched filters cannot be affordable due to the resource limitation. Second, matched filter method requires a priori knowledge about PU transmission, i.e., power level, modulation type, signal characteristics, and synchronization with PU. However, in real life, CRSN will operate opportunistically over licensed channels. To enable time synchronization with PU is extremely challenging without obtaining the information that PU is active on the channel or not. Furthermore, additional energy consumption is required to search for PU statistics and transmission knowledge. Hence, these disadvantages make this approach as an unfeasible spectrum sensing solution for CRSN.

The second main sensing approach is energy detection [43], [49]. The methods based on energy detection do not require a priori PU knowledge and excessive computational power. On the other hand, there are two major drawbacks of energy detection, first the algorithm of energy detection runs based on constant and known noise variation. However, in reality, knowledge of noise variation without any environmental information is very challenging. Second, low level of SNR has an aggravating effect on energy detection performance.

Another approach is feature or cyclostationary detection which enables to separate noise and PU signal [8]. Additionally, cyclostationary detection methods operate optimal in the circumstances of low SNR. However, the most important shortcoming of feature detection approach is the requirement of a priori PU knowledge.

3.3.2 Energy Detection Method

With respect to abovementioned sensing approaches, although it has inaccurate results under noise variations, energy detection stands as the best solution for CRSN. Energy detector uses energy of received signal to decide whether PU is on the channel or not. It usually collects samples on frequency bands and calculates the energy of obtained samples. Detection classifies two states which are H_0 and H_1. H_0 represents the vacant time of a channel and H_1 denotes PU transmission. Energy detector compares the energy of obtained samples to predetermined threshold according to these two states and makes a decision. In [15], optimal spectrum sensing method is developed for cognitive radio networks. In the model, 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 [15]

$$Pr_f(B, t_s, Pr_{off}) = Pr_{off} Q(\frac{\lambda - 2t_s B\sigma_n^2}{\sqrt{4t_s B\sigma_n^4}}) \tag{3.1}$$

$$Pr_d(B, t_s, Pr_{on}) = Pr_{on} Q(\frac{\lambda - 2t_s B(\sigma_s^2 + \sigma_n^2)}{\sqrt{4t_s B(\sigma_s^4 + \sigma_n^4)}}) \tag{3.2}$$

where Pr_{on} and Pr_{off} are on and off probabilities, respectively, B is bandwidth of channel, λ is threshold value, σ_s^2 and σ_n^2 are PU signal and noise variances, respectively, t_s is sensing time and Q function is

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{u^2}{2}} \mathrm{du} \tag{3.3}$$

In CRSN, it is already mentioned that every CRSN node is assumed to have ability to sense all the frequency bands on which the network operates. Additionally, in [43], (3.1) and (3.2) are used for cognitive sensor network to find optimal number of sensor node which participates sensing process. In our work, we use (3.1) and (3.2) to determine the detection and false alarm channel state probabilities which will be discussed in Section 3.5.

3.3.3 Analysis of Energy Detection Parameters

The parameters that affect energy detection sensing probabilities are discussed below and impact of the variation of these parameters on Pr_d and Pr_f is analyzed.

- **Sensing time (t_s)**: As a result of hardware limitation, CRSN nodes cannot perform spectrum sensing and transmission simultaneously. First, a node senses all network channels in sensing period, then, adjusts its transmission parameters accordingly, and finally, it starts communicating. While moving around cognitive cycle periods mentioned in Section 3.1.2.2, a tradeoff between transmission time and spectrum sensing time arises. Transmission time needs to be as long as possible for the sake of vacant time utilization and QoS requirements of CRSN. Event-driven nature of sensor networks requires real-time and massive data transfer to detect an event. Naturally, longer transmission time imposes longer packet size. However, extension of a transmission time to achieve required data transmission undermines the period of spectrum sensing time which causes reduction of number of observation samples. CRSN strongly requires high level of Pr_d while keeping Pr_f as low as possible in order to remain under the acceptable interference level that PU can tolerate. Therefore, accurate sensing time needs to be set for satisfying both requirements of high level of Pr_d and real-time massive data transfer in CRSN.

- **Signal-to-noise ratio (SNR)**: High level of SNR increases PU detection on channels and leads to high Pr_d. However, the noise variations yield changes in SNR value. Consequently, these variations affect the performance of energy detector. On the other hand, in case of misdetection high level of SNR causes high levels of interference to CRSN node that hampers its communication reliability.

- **Operating frequency band (f)**: Different operating frequency bands exhibit different characteristics and induce different path loss patterns that yield distinctive SNRs. Even if all the other parameters of network are fixed, SNR values on two spectrum bands are different. When CRSN operates on high frequency bands, path loss propagation becomes sharp and decreases Pr_d. In other words, operating over the low frequency bands increases the probability of successful detection of PU over spectrum band.

- **Threshold value (λ)**: Energy detector decides on the availability of channels according to threshold value. λ can be obtained by means of numerical methods and calculated in order to succeed the target Pr_d and Pr_f. Due to the heterogeneous application-specific requirements, threshold value must be accurately calculated, which is a challenging task. Hence, λ is an application- specific parameter and variations at λ have direct influence on Pr_d and Pr_f.

- **PU behavior (v_p, l_p)**: The main parameter is PU activity pattern for detection and false alarm probabilities. (3.1) and (3.2) impose that Pr_d cannot be larger than Pr_{on}, Pr_f value cannot exceed the probability that PU is absent. They both make sense because PU cannot be detected when it is not actually on the channel and false alarm cannot occur when channel is used by PU.

3.4 Dynamic Spectrum Access for CRSN

After obtaining available channel information through energy detection method, spectrum access function steps in for capturing transmission opportunity. Fundamentally, dynamic spectrum access provides a frequency band and opportunistic transmission time for CRSN nodes. With regard to this, in this section, first we explore the existing medium access control (MAC) approaches based on their suitability for CRSN. Then, according to assumed approach, we present the dynamic spectrum access model. Afterwards, the channel states are defined with respect to dynamic spectrum access model.

3.4.1 Analysis of Existing MAC Approaches

There are two main approaches for MAC in CR networks. First one is the infrastructure-based access protocols that operate with central entity and also via control channel. In this case, a central controller is responsible for coordination and synchronization among CRSN nodes. All information about CRSN is supplied by central entity to all CRSN nodes. Infrastructure-based access protocols are applicable to cellular wireless networks because nodes usually communicate with a central authority, i.e., access point or base station, in a single hop in these type of networks. In a sensor field, communicating with a central entity in a single hop is an unrealistic assumption due to ad hoc and randomly deployed structure of CRSN. In some cases, central entity such as base station or super powered node allows the concurrent transmission of secondary and primary users by adjusting the output power and data rate of SU. Violation of PU needs to be clearly analyzed for these concurrent cases.

The second main approach is the decentralized access that enables CRSN nodes to search spectrum holes independently without a central controller. These protocols support scalability and flexible deployment. Due to the event-driven and application-specific nature of sensor networks, decentralized protocols stand as feasible solutions. For our CRSN model, time-slotted decentralized MAC mechanism is adopted.

In Figure 3.3, the channel access scheme of CRSN nodes is presented and the number of channels (C) is assumed to be 4. When an event occurs, source signal is generated. CRSN nodes detect the event signal, process it and generate data packets to send. Then, they search for an available channel to access. Basic DSA model, in Figure 3.3, is as follows. Each time slot can be split up to three main sub time 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, CRSN node decides which spectrum band to operate. If the band that is already used by CRSN node on the previous slot is identified as available channel, CRSN node does not change its operating frequency and continues its transmission on the same band. Otherwise, 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

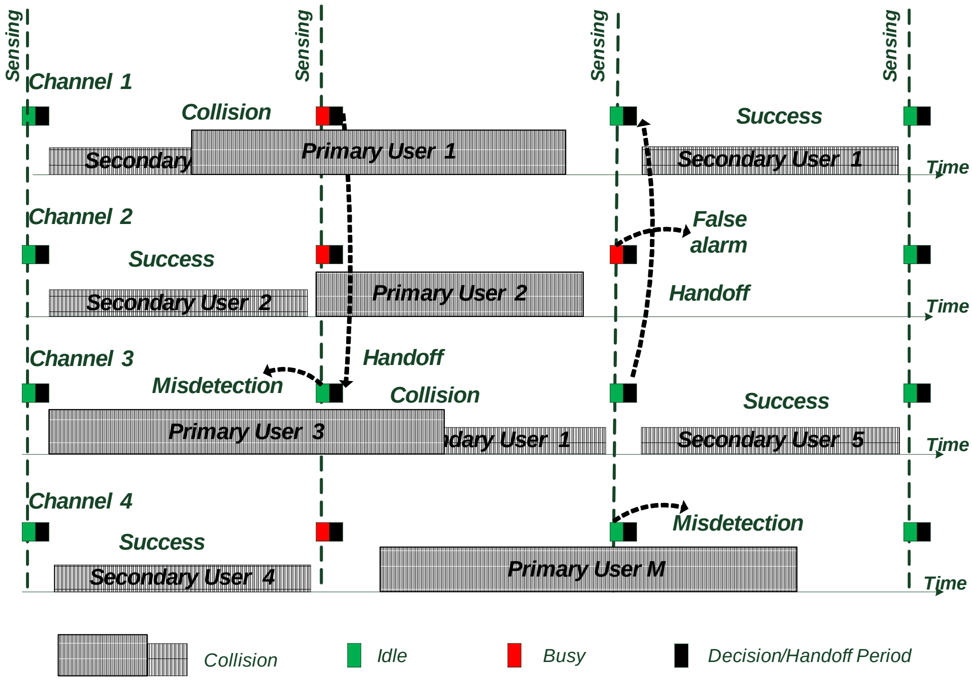

Figure 3.3: General Dynamic Spectrum Access Scheme for CRSN.

hole at spectrum sensing time period. Actual transmission time appears in the last sub time period.

It is assumed that CRSN node can transmit only one data 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, it recognizes that data packet which is sent in the previous slot is corrupted. As a result, sensor node retransmits the lost packet in the next time slot. This CR-MAC mechanism contains all main functionalities of cognitive cycle such as spectrum sensing, decision and handoff.

The definition of channel states and analysis of corresponding bit error rates (BER) are necessary for energy-efficient packet size optimization. According to the operational concept of DSA as mentioned in Section 3.4.1, whenever CRSN node has data packets to send, the six different states may occur on one channel. These states are shown in Figure 3.4 and overviewed below.

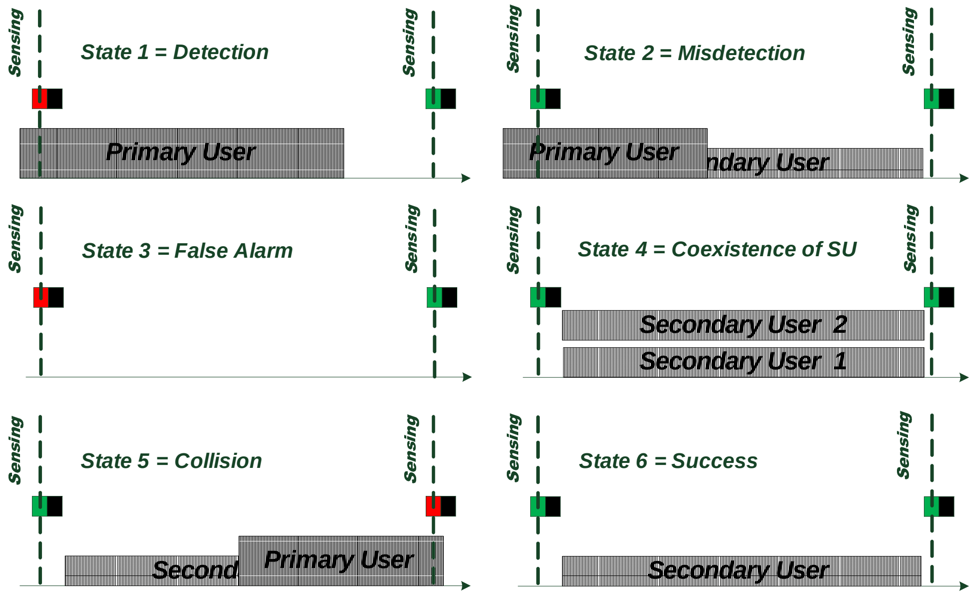

Figure 3.4: States of Channel for CRSN under DSA.

3.4.2 Channel States under DSA

- **Detection State (State 1)**: CRSN node senses all channels and infers the presence of PU on the channel used for transmission during the last time slot. According to sensing results, CRSN node decides and moves along a new channel to operate in the next transmission period.

- **Misdetection State (State 2)**: Misdetection of PU is one of the worst states on channel for CRSN node. CRSN node senses a channel and erroneously infers that the channel is available to communicate. However, in reality, the channel is already occupied by PU. Thus, primary and secondary users start to communicate at the same time in network, SU parameters are not tailored regarding to PU interference because SU supposes that the channel is idle for transmission. Due to the concurrent transmission, data packets of both users collide and produce penalty for each other. The probability of missing PU affects BER calculations, and hence, packet size. BER values dramatically increase which may yield lost data packets in misdetection state. Therefore, it is beneficial to stop transmission for both sides. However, SU cannot be aware of presence of PU until the next sensing duration. Thus, energy-efficient packet size optimization must ensure that misdetection state of channel is considered.

- **False Alarm State (State 3)**: False alarm state is mainly the reverse of misdetection state. CRSN node senses a channel and incorrectly assumes that it is already owned by PU. However, in reality channel was open to communicate for CRSN node. Thus, channel may remain as empty for all slot transmission time. Idle time wastage of a channel undermines the utilization and opportunistic access of channel.

- **CRSN Nodes Coexistence State (State 4)**: Coexistence of SUs on the same band is a result of decentralized access approach. There is no control channel or central entity to coordinate all CRSN nodes. Therefore, after the observation of an event, two or more independent CRSN nodes may select the same channel to communicate. Coexistence of CRSN nodes is highly dependent on the number of network channels and CRSN nodes. Although decentralized access approach causes this state, it provides flexibility and scalability which are more crucial priorities for CRSN.

- **Collision State (State 5)**: A CRSN node senses all channels of network and identifies one of them as an available band to communicate in the state of collision. Then, it starts to transmit a data packet according to sensing result. However, PU appears and communicates on the channel in the range of transmission time of CRSN node. It is already assumed that CRSN nodes cannot proceed sensing while transmitting a data packet. Thus, the presence of PU during the transmission time cannot be immediately recognized. Due to hardware limitation of CRSN node, PU transmission can be detected only during the sensing period. The arrivals of PU during CRSN node communication hampers the reliability of packet transmission and increases BER for both users. It is always preferable to have longer transmission time because it maximizes energy-efficiency of CRSN node. On the other hand, longer transmission time entails to increase probability of collision between primary and secondary users.

- **Success State (State 6)**: All processes in CRSN are performed to realize and maintain the state of success as the ultimate objective of all CR networks is to achieve reliable and successful communication for SUs. The procedure of success state on channel is as follows. CRSN node senses all network channels, and successfully selects one of unoccupied channels to communicate. If PUs do not interrupt transmission, it is assumed that data packet transmission conditions are the same as PUs. State of success on channel is closely related on five previous states. Altering any parameter of these five states affects the state of success directly.

3.5 Channel State Probabilities and BER Analysis

In this part, channel state probabilities, i.e., probability of the channel is in state i as explained in Section 3.4.2, Pr_i, are defined and analyzed. It is shown in Figure 3.4 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.,

$$Pr_{on} = Pr_1 + Pr_2 \tag{3.4}$$

In contrast, states 3 to 6 can be realized when the channel is idle. Although CRSN node defines that the channel is in the service of PU, false alarm state occurs when PU is actually not on the channel. Additionally, more than one sensor nodes sense and determine that the channel is not captured by PU in the state of SUs coexistence. Furthermore, at the collision state, channel is defined as idle at sensing time. It is obvious that to achieve successful communication between CRSN nodes, PUs should have no transmission activity on the channel. As a result, total probability of these four states should be equal to the probability that the PU is in OFF state,i.e.,

$$Pr_{off} = Pr_3 + Pr_4 + Pr_5(l_s) + Pr_6(l_s) \tag{3.5}$$

At CRSN point of view, individual channel state probabilities need to be investigated in order to derive an average BER formulation. Therefore, we start with probability of detection state which can be expressed as (3.2). Then, by subtracting (3.4) from (3.2), the probability of misdetection state can be calculated as

$$Pr_2(B, t_s, Pr_{on}) = Pr_{on}\left[1 - Q(\frac{\lambda - 2t_sB(\sigma_s^2 + \sigma_n^2)}{\sqrt{4t_sB(\sigma_s^4 + \sigma_n^4)}})\right] \tag{3.6}$$

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 (3.1). 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.

It is already assumed in Section 3.2 that PU behavior is stationary and ergodic for every channel of network. Therefore, the number of available channels for 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

$$Pr_4 = (Pr_{off} - Pr_3)\left[1 - (\frac{v_p(C-1) - l_p}{Cv_p})^{M-1}\right] \tag{3.7}$$

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

After formulating the probability of CRSN nodes coexistence on the same channel, the probability of collision state needs to be studied. It is reasonable to suppose that PU packet size is much longer than CRSN node packet size. Hence, more than one packet of PU cannot be transmitted in the range of CRSN node transmission period.

In CRSN, the usage of fixed packet size is selected instead of adaptive packet size because using adaptive packet size ruins synchronization between SUs and also increases the energy consumptions. In our CRSN, l_s and R denote fixed packet size and data rate of CRSN node, respectively. Since idle time of a channel 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

$$Pr(Collision) = 1 - \int_{\frac{l_s}{R}}^{\infty} \frac{1}{v_p} e^{-\frac{t}{v_p}} \mathrm{dt} = 1 - e^{-\frac{l_s}{Rv_p}} \tag{3.8}$$

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

$$Pr_5(l_s) = (1 - e^{-\frac{l_s}{Rv_p}})(Pr_{off} - Pr_3 - Pr_4), \tag{3.9}$$

$$Pr_6(l_s) = e^{-\frac{l_s}{Rv_p}}(Pr_{off} - Pr_3 - Pr_4). \tag{3.10}$$

In [23], the United States Federal Communications Commission (FCC) states that the usage of spectrum is in the range of 15% to 85% with respect to geographical variations in the old fashion static access. With regard to this, we use different Pr_{on} values in our numerical analysis in order to investigate the effects of primary user behavior. Figure 3.5 and Figure 3.6 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 Figure 3.5 and Figure 3.6 that, increasing sensing time reduces the misdetection state probability but raises the probability false alarm state which yields a decrease in the probability of successful transmission. Therefore, detection and false alarm states probabilities should be adjusted to enable accurate successful transmission for CRSN node.

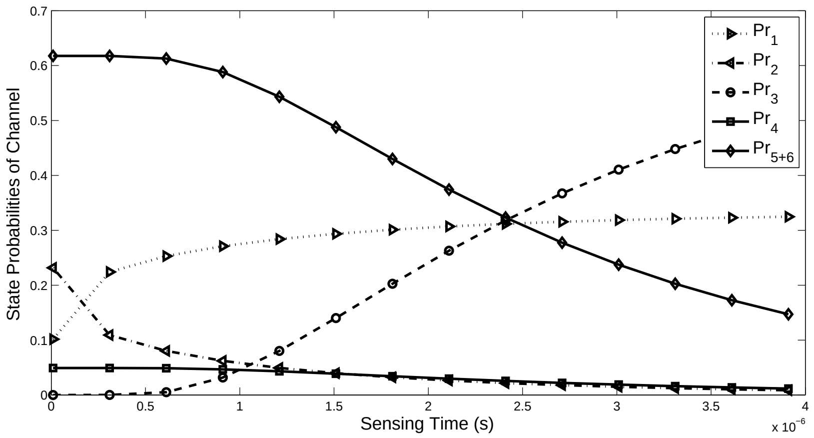

Figure 3.5: Variation of channel state probabilities with respect to sensing time when $Pr_{on} = \frac{1}{3}$.

Next, we estimate the average BER. An accurate BER derivation is essential for energy-efficient packet size optimization. As mentioned in Section 1.1, rather than conventional layered networking, CRSN necessitates cross-layer design approach. With regard to dynamic spectrum access, the performance of the communication protocols is highly related to the spectrum decisions, and spectrum sensing results. There-

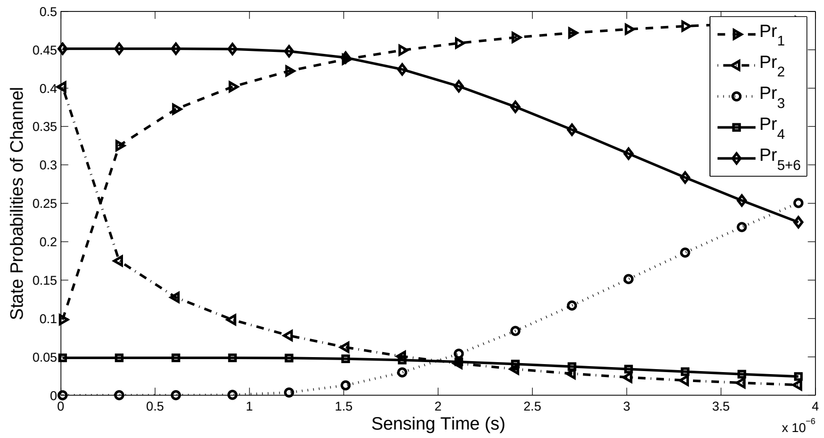

Figure 3.6: Variation of channel state probabilities with respect to sensing time when $Pr_{on} = \frac{1}{2}$.

fore, BER relies on physical channel conditions and modulation type in traditional networks, for CRSN, BER is also dependent on the sensing results and the MAC protocols of network. Hence, simple approach to calculate average BER for a channel under DSA is as follows. There are six different states that a channel can be in during dynamic spectrum access. Therefore, average BER of a channel is

$$\Lambda(l_s) = \sum_{i=1}^{6} Pr_i \Lambda_i \tag{3.11}$$

where Λ denotes BER. Classically, BER value is closely related to distance between transmitter and receiver and also output power of transmitter in typical wireless networks. It can be seen in (3.11) that BER value of CR networks additionally depends on packet size of SUs as well. Variation of packet size affects BER value in the sense that the probability of collision increases with packet size. With the interpretation of (3.11), it can be seen that in detection and false alarm states of channel, CRSN nodes actually do not transmit. Therefore, for these channel states, BER does not exist. Hence, removing these two state probabilities and normalizing the remaining probabilities are necessary to obtain an accurate BER result, i.e.,

$$\Lambda(l_s) = \sum_{i=1}^{6} \frac{Pr_i \Lambda_i}{\sum_{j=1}^{6} Pr_j} \tag{3.12}$$

where $i,j \neq 1, 3$. Thus, for a CRSN node, BER of a channel is dependent on its own packet size.

3.6 Reliable Event Signal Estimation at Sink in CRSN

The main purpose of densely deployed CRSN is to reliably detect and estimate an event from collective information provided by each node while maintaining the acceptable interference level for PU. In the event area, each CRSN node observes the noisy version of the tracked signal which needs to be regenerated at sink node. Sink node is just interested in the estimation of the tracked event signal via data packets that are collected from CRSN nodes. 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. Therefore, the requirement of maximum allowed distortion level between event signal and its estimation must be considered at the energy-efficient packet size optimization in order to assure reliability.

Based on the estimation of the physical phenomena, sink node must decide on actions for CRSN in range of short time interval which can be described as τ_d. Determination of τ_d depends on application-specific requirements, and hence, is left beyond the scope of this work.

Since each CRSN node observes noisy version of the same event signal, 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. Therefore, instead of all nodes transmismitting, selecting the source nodes to transmit brings significant advantages in the sense of reducing congestion, network load, packet traffic and energy consumption. Hence, traditional end-to-end reliability models are insufficient for our CRSN due to the spatial and temporal correlation. As a matter of fact, in [11], a new notion of reliable and real-time event-to-sink transport protocol is introduced for traditional WSN. Reliable and collective transport of event features from sensor field to sink node is presented. However, this transport protocol is not applicable to the CRSN regime, as it does not consider spectrum agility.

Due to noise variations, packet losses and spatial deployment of sensor field, the sink observes distorted version of the tracked event signal. In [16], distortion metric between actual event signal and its estimation at sink is derived assuming that event signal is a Gaussian random process. It can be given as [16]

$$D(M) = \sigma_s^2 - \frac{\sigma_s^4}{M(\sigma_s^2+\sigma_n^2)}(2\sum_{i=1}^{M}\rho_{(i,s)} - 1) + \frac{\sigma_s^6}{M^2(\sigma_s^2+\sigma_n^2)^2}\sum_{i=1}^{M}\sum_{j\neq i}^{M}\rho_{i,j}. \quad (3.13)$$

where $D(M)$ is distortion metric and M is the number of nodes which sense the event signal and successfully deliver their readings to the sink. It can be seen in (3.13) that the number of the represantative 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

$$M^* = \arg\min_{M} (D(M) \leq D_{max}) \quad (3.14)$$

where D_{max} is the maximum allowed distortion.

After deciding an the number of source sensor nodes, the total amount of payload bits which are generated during sampling of tracked event signal, needs to be calculated in order to decide on the range of packet size in terms of bits. In CRSN, the tracked event can be characterized as single point source. Since B_s denotes the bandwidth of the source signal, CRSN node sampling frequency should be at least $2B_s$ with respect to Nyquist sampling theorem to recover source signal back at CRSN node thereby, at sink. In the observation time (τ_s), sensors take the samples of the signal generated by physical phenomena. Then, Analog to Digital Converter (ADC) of CRSN node converts each sample to χ bits. As a result, each CRSN node has $2\tau_s B_s \chi$ number of payload bits to send to sink through CRSN. Packet size of CRSN node should be determined to assure that $2\tau_s B_s \chi$ bits of each source CRSN node must reach sink before τ_d ends. Therefore, requirement of reliable event signal estimation at sink must be considered in the determination of energy-efficient packet size for CRSN.

After modeling our CRSN architecture with respect to algorithms and designs devised for cognitive radio and sensor networks, in the next chapter, we focus on the energy-efficient packet size optimization problem for this architecture.

CHAPTER 4

ENERGY-EFFICIENT PACKET SIZE OPTIMIZATION IN CRSN

In the previous section, we outline the architecture of our CRSN model. The model of CRSN node energy consumption, PU behavior, spectrum sensing method, MAC protocol and channel states under DSA in CRSN, channel state probabilities and BER for CRSN nodes are presented. In this section, we state the problem definition of energy-efficient packet size optimization, then, we derive the optimization problem formulation.

4.1 Problem Definition

In this thesis, we formulate the problem of optimal packet size which maximizes the energy-efficiency for CRSN node while maintaining acceptable interference level for PU and remaining under the distortion level between tracked signal and its estimation at sink node. To formulate this problem, following definitions are essential.

Definition 1: k_1 is the total power consumption of transferring one packet to 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 expended energy to transmit/receive a packet and can be expressed as

$$\eta(l_s) = \frac{k_1 l_s}{k_1 l_s + k_2 R} \tag{4.1}$$

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

$$r(l_s) = [1 - \Lambda(l_s)]^{l_s} \tag{4.2}$$

where $\Lambda(l_s)$ is as given in (3.12).

Definition 3: $I_p(l_s, l_p)$ is 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 (3.14).

According to these definitions, energy-efficient packet size optimization problem can be formulated as

$$\begin{aligned} \underset{l_s}{\text{maximize}} \quad & \eta(l_s)r(l_s) \\ \text{subject to} \quad & I_p(l_s, l_p) \leq I_{max} \\ & \tau_g(l_s, M^*) \leq \tau_d \end{aligned} \tag{4.3}$$

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 ($k_2 + k_1 \frac{l_s}{R}$). Therefore, energy throughput and reliability metrics need to be evaluated jointly to determine energy-efficiency of CRSN node. Hence, energy-efficiency metric is defined in (4.3) as an objective function that corresponds to the multiplication of energy throughput and reliability metrics.

The l_s value maximizing the objective function in (4.3) is determined as the energy-efficient packet size when it also meets constraints ($I_p(l_s, l_p) \leq I_{max}, \ \tau_g(l_s, M^*) \leq \tau_d$) of (4.3). Contrarily, when l_s value maximizing the objective function does not satisfy the constraint equations of (4.3). Then, new l_s value is selected as the optimal packet size that satisfies the constraint equations of (4.3).

4.2 Objective Function of Optimization Problem

4.2.1 Derivation of Energy-Efficiency Metric

We define the objective function of packet size optimization problem in (4.3). The objective function corresponds to the multiplication of energy-efficiency and reliability metric. Hence, for the accurate calculation of optimal packet size, energy-efficiency metric, which is stated in (4.1), needs to be studied and its parameters need to be investigated. Therefore, next, we investigate k_1 and k_2 parameters in (4.1).

In [32], [39], it is shown that the required energy to transfer a packet from one CRSN node to other is sum of transmitting and receiving energy. E_p is represented as the required energy and expressed as

$$E_p = E_r + E_t \tag{4.4}$$

where E_r and E_t denote the energy consumption of receiving and transmitting a packet, respectively. 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 3.1.2, need to be calculated. In Figure 3.2, power level and time interval of each period and transition time between periods are depicted. Therefore, energy consumed in period i can be given as $E_i = P_i \tau_i$. However, it can be seen in Figure 3.2 that consumed power of CRSN node varies during transition times. To overcome this problem, average energy consumption during these phases is calculated as

$$E_{i,j} = \frac{(P_i + P_j)\tau_{ij}}{2} \tag{4.5}$$

where $E_{i,j}$ is energy consumption during transition time, P_i and P_j are consumed powers in periods i and j, respectively, and τ_{ij} is the transition time between period i to period j. Hence, E_r of CRSN node can be written as

$$E_r = \frac{P_5 + P_1}{2}\tau_{51} + P_1 \frac{l_s}{R} \tag{4.6}$$

At receiving part, CRSN node waits in ready period then moves to receive period to collect a packet. On the other hand, at transmitting part, when the event is observed, 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}. In fact, unlike the traditional sensor networks, PU behavior affects the energy consumption of CRSN node. According to sensing outcomes, CRSN node either switches to handoff period or moves directly to transmit period. Hence, energy consumed during transmission is

$$\begin{aligned} E_t(Pr_{off}) &= \frac{P_5+P_4}{2}\tau_{54} + P_4\tau_{se} + \frac{P_4+P_3}{2}\tau_{43} + P_3\tau_{de} + \\ & Pr_{off}\left[P_3(\tau_{32}+\tau_{hf}) + \frac{P_3+P_0}{2}\tau_{30} + P_0\frac{l_s}{R}\right] + \\ & Pr_{on}\left[\frac{P_3+P_2}{2}\tau_{32} + P_2\tau_{hf} + \frac{P_2+P_0}{2}\tau_{20} + P_0\frac{l_s}{R}\right] \end{aligned} \tag{4.7}$$

where τ_{se}, τ_{de}, τ_{hf} are the cognitive cycle periods corresponding to sensing, decision, handoff periods, respectively. To proceed further, (4.7) can be restated as

$$\begin{aligned} E_t(Pr_{off}) &= P_5(\frac{\tau_{54}}{2}) + P_4(\frac{\tau_{54}}{2} + \tau_{se} + \frac{\tau_{43}}{2}) + \\ & P_3\left[\frac{\tau_{43}}{2} + \tau_{de} + Pr_{on}\frac{\tau_{32}}{2} + Pr_{off}(\frac{\tau_{30}}{2} + \tau_{32} + \tau_{hf})\right] + \\ & P_2Pr_{on}(\frac{\tau_{32}}{2} + \tau_{hf} + \frac{\tau_{20}}{2}) + P_0(Pr_{off}\frac{\tau_{30}}{2} + Pr_{on}\frac{\tau_{20}}{2}) + P_0(\frac{l_s}{R}) \end{aligned} \tag{4.8}$$

For simplification, we denote E_{t4}, $E_{t3}(Pr_{off})$, $E_{t2}(Pr_{off})$ to correspond total energy consumption for sensing, decision, handoff functions, respectively. They can be expressed as below

$$\begin{aligned} & E_{t4} = P_4(\frac{\tau_{54}}{2} + \tau_{se} + \frac{\tau_{43}}{2}) \\ & E_{t3}(Pr_{off}) = P_3\left[\frac{\tau_{43}}{2} + \tau_{de} + Pr_{on}\frac{\tau_{32}}{2} + Pr_{off}(\frac{\tau_{30}}{2} + \tau_{32} + \tau_{hf})\right] \\ & E_{t2}(Pr_{off}) = P_2(1 - Pr_{off})(\frac{\tau_{32}}{2} + \tau_{hf} + \frac{\tau_{20}}{2}) \end{aligned} \tag{4.9}$$

Therefore, energy consumed during transmission is

$$\begin{aligned} E_t(Pr_{off}) &= P_5(\frac{\tau_{54}}{2}) + E_{t4} + E_{t3}(Pr_{off}) + E_{t2}(Pr_{off}) + \\ & P_0(Pr_{off}\frac{\tau_{30}}{2} + Pr_{on}\frac{\tau_{20}}{2}) + P_0\frac{l_s}{R} \end{aligned} \tag{4.10}$$

According to (4.6) and (4.10), E_p is

$$\begin{aligned} E_p &= \frac{P_5\tau_{54}}{2} + E_{t4} + E_{t3}(Pr_{off}) + E_{t2}(Pr_{off}) + \\ & P_0(Pr_{off}\frac{\tau_{30}}{2} + Pr_{on}\frac{\tau_{20}}{2}) + P_0\frac{l_s}{R} + \frac{P_5+P_1}{2}\tau_{51} + P_1\frac{l_s}{R} \end{aligned} \tag{4.11}$$

with respect to (4.11) and definition 1, k_1 and k_2 parameters in (4.1) are

$$k_1 = P_0 + P_1$$
$$k_2 = E_5 + E_{t4} + E_{t3}(Pr_{off}) + E_{t2}(Pr_{off}) + P_1\frac{\tau_{51}}{2} + P_0(Pr_{off}\frac{\tau_{30}}{2} + Pr_{on}\frac{\tau_{20}}{2}) \quad (4.12)$$

where $E_5 = P_5(\tau_{54} + \tau_{51})/2$. As a result, the parameters of energy-efficiency metric are completely obtained.

4.2.2 Derivation of Packet Reliability Metric

4.2.2.1 Definition of BER types

Packet reliability metric is introduced in definition 2. Basically, it is the probability that all bits of one packet are received correctly. In this part, we examine (3.12) and (4.2) in detail for accurate calculation of packet size optimization problem. $\Lambda(l_s)$ in (3.12) 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 Figure 3.4, when the states are carefully examined, it is observed that a CRSN node may experience two different types of BER on channel, which are summarized below:

- $\Lambda_S(\gamma_a)$: $\Lambda_S(\gamma_a)$ is bit error rate on the channel when CRSN node does not encounter any other transmissions on channel where γ_a is signal-to-noise ratio. $\Lambda_S(\gamma_a)$ is traditionally related to distance between CRSN nodes and output powers.
- $\Lambda_I(\gamma_b)$: $\Lambda_I(\gamma_b)$ is bit error rate of channel when CRSN node encounters another transmission on channel where γ_b is signal-to-noise ratio. In addition to distance between CRSN nodes and output powers, $\Lambda_I(\gamma_b)$ is also related to either PU or SU distance and output power.

4.2.2.2 BER in channel states

Transmission between CRSN nodes on channel occurs in four channel states. The total average BER of these four channel states are derived in terms of $\Lambda_I(\gamma_b)$ and

$\Lambda_S(\gamma_a)$ below.

- **BER in Success State (State 6)**

  CRSN node does not encounter any other simultaneous transmission on the channel. Consequently, it is reasonable to assume that Λ_S is the actual bit error rate for the success state of channel which can be represented as

$$\Lambda_6 = \Lambda_S(\gamma_a) \tag{4.13}$$

- **BER in Coexistence State (State 4)**

  If two or more CRSN nodes transmit simultaneously, then the channel is in coexistence state. In this case, CRSN node experiences interference caused by another secondary user transmission on channel throughout the entire transmission period. Therefore,

$$\Lambda_4 = \Lambda_I(\gamma_b) \tag{4.14}$$

- **BER in Misdetection State (State 2)**

  In misdetection state, CRSN nodes certainly experience the PU interference on channel. However, the duration of the interference experienced varies. It may either last for the entire transmission period or finish before CRSN node transmission ends. The probability that PU stops transmission before the end of CRSN node transmission period can be calculated as

$$1 - \int_{\frac{l_s}{R}}^{\infty} \frac{1}{l_p} e^{-\frac{t}{l_p}} \mathrm{dt} = 1 - e^{-\frac{l_s}{Rl_p}} \tag{4.15}$$

  where l_s and R are fixed packet size and data rate of CRSN node, respectively, and l_p is the mean of channel busy time. Consequently, 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 CRSN node ends, in [43], it is shown that the average time that PU stays on the channel, during the transmission period of a CRSN node converges to $Pr_{on}\frac{ls}{R}$. As a result, the average BER in misdetection state on channel can be calculated as

$$\Lambda_2(l_s) = \Lambda_I(\gamma_b)[Pr_{on} + Pr_{off}e^{\frac{-l_s}{Rl_p}}] + \Lambda_S(\gamma_a)[Pr_{off}(1 - e^{\frac{-l_s}{Rl_p}})] \tag{4.16}$$

  where Pr_{on} and Pr_{off} are on and off probabilities, respectively, l_s and R are fixed packet size and data rate of CRSN node, respectively, and l_p is the mean of channel busy time.

- **BER in Collision State (State 5)**

  In collision state, CRSN node senses the channel, identifies correctly that the channel is idle and begins its transmission. However, PU returns to its band before CRSN node transmission ends. Naturally, it is assumed that PU packets are much longer than CRSN node packets. Consequently, the event that PU transmission finishes before the end of CRSN node transmission period is ignored for collision state of channel. It is already mentioned in misdetection state that the time duration of PU occupancy on channel converges to $Pr_{on}\frac{l_s}{R}$ during the CRSN node transmission period. Therefore, BER of collision state of channel can be given as

$$\Lambda_5 = \Lambda_I(\gamma_b)Pr_{on} + \Lambda_S(\gamma_a)Pr_{off} \tag{4.17}$$

4.2.2.3 Derivation of total average BER expression

Since the BER expressions of all possible channel states are derived, inserting (4.13), (4.14), (4.16) and (4.17) into (3.12), the total average BER that is experienced by a CRSN node,i.e.,$\Lambda(l_s)$, can be expressed as

$$\begin{aligned}\Lambda(l_s, \gamma_a, \gamma_b) \;=\; & \frac{1}{Pr_2 + Pr_4 + Pr_5 + Pr_6} \\ & [\Lambda_I(\gamma_b)(Pr_2 Pr_{on} + Pr_2 Pr_{off} e^{\frac{-l_s}{Rl_p}} + Pr_4 + Pr_{on}Pr_5) + \\ & \Lambda_S(\gamma_a)(Pr_2 Pr_{off}(1 - e^{\frac{-l_s}{Rl_p}}) + Pr_{off}Pr_5 + Pr_6]\end{aligned} \tag{4.18}$$

As $Pr_5 + Pr_6 = Pr_{off} - Pr_3 - Pr_4$, and further simplifying, (4.18) can be rewritten as

$$\Lambda(l_s, \gamma_a, \gamma_b) = \Lambda_S(\gamma_a) + c_1 \left[\frac{Pr_2(Pr_{on} + Pr_{off}e^{\frac{-l_s}{Rl_p}}) + Pr_4 + Pr_{on}Pr_5(l_s)}{Pr_{off} + Pr_2 - Pr_3} \right] \tag{4.19}$$

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. In [19], an adaptive multi-carrier modulation strategy is introduced which aims to maximize the network lifetime by selecting the optimal constellation size for CRSN. Inversely, in [32], it is shown that when the start-up times are long, which may well be the actual case in CRSN, M-ary modulations become energy-inefficient for sensor networks. According to [31], [39], it is reasonable to assume that CRSN node employs binary orthogonal frequency shift keying (FSK) modulation on a frequency non-selective Rayleigh fading channel. The BER for non-fading channel and FSK can be expressed as [36]

$$\Lambda(\gamma) = \frac{1}{2}e^{-\gamma/2} \tag{4.20}$$

With regard to (4.20), we must average $\Lambda(l_s, \gamma_a, \gamma_b)$ given in (4.19) over the probability density functions of γ_a and γ_b.

$$\Lambda(l_s) = \int_0^\infty \int_0^\infty \Lambda(l_s, \gamma_a, \gamma_b) p(\gamma_a) p(\gamma_b) \mathrm{d}\gamma_\mathrm{a} \mathrm{d}\gamma_\mathrm{b} \tag{4.21}$$

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

$$p(\gamma_a) = \frac{1}{\overline{\gamma_a}}e^{-\gamma_a/\overline{\gamma_a}} \tag{4.22}$$

$$p(\gamma_b) = \frac{1}{\overline{\gamma_b}}e^{-\gamma_b/\overline{\gamma_b}} \tag{4.23}$$

where $\overline{\gamma_a}$ and $\overline{\gamma_b}$ are average of γ_a and γ_b respectively. According to (4.22), (4.23) and (4.19), (4.21) can be rewritten as

$$\Lambda(l_s) = \int_0^\infty \int_0^\infty \left[\frac{1}{2}e^{-\gamma_a/2} + (\frac{1}{2}e^{-\gamma_b/2} - \frac{1}{2}e^{-\gamma_a/2})\Upsilon(l_s)\right] \frac{1}{\overline{\gamma_a}}e^{\gamma_a/\overline{\gamma_a}} \frac{1}{\overline{\gamma_b}}e^{\gamma_b/\overline{\gamma_b}} \mathrm{d}\gamma_\mathrm{a} \mathrm{d}\gamma_\mathrm{b} \tag{4.24}$$

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

$$\Lambda(l_s) = \frac{1}{2+\overline{\gamma_a}} + \Upsilon(l_s)(\frac{\overline{\gamma_a} - \overline{\gamma_b}}{(2+\overline{\gamma_b})(2+\overline{\gamma_a})}) \tag{4.25}$$

where $\overline{\gamma} = E[\alpha^2]\frac{E_b}{N_o}$. 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 a 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 value is traditionally computed with SNR. Hence, $\frac{E_b}{N_o}$ of γ_a can be expressed as [27],

$$\frac{E_b}{N_o} = \frac{SNR}{R} = \frac{P_{rs}}{N_o R} \tag{4.26}$$

where N_o is the noise power density and P_{rs} is received power of CRSN node transmitter. On the other hand, $\frac{E_b}{N_o}$ of γ_b can be given as [30],

$$\frac{E_b}{N_o} = \frac{SINR}{R} = \frac{P_{rs}}{(N_o + P_{rp})R} \tag{4.27}$$

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

$$P_{rs}(d_{ss}) = \frac{P_s G_t G_r \lambda^2}{(4\pi)^2 L d_{ss}^{\delta} 10^{(X_\sigma/10)}} \tag{4.28}$$

$$P_{rp}(d_{sp}) = \frac{P_p G_t G_r \lambda^2}{(4\pi)^2 L d_{sp}^{\delta} 10^{(X_\sigma/10)}} \tag{4.29}$$

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 [34],[37].

4.2.2.4 Energy-efficiency performance of CRSN node with varying packet size

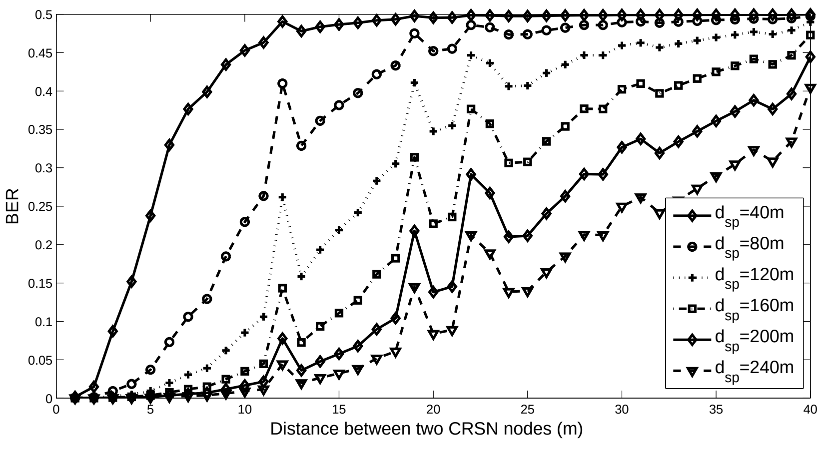

Figure 4.1: BER vs. distance between two CRSN nodes under different PU distances.

Figure 4.1 illustrates the behavior of BER when distance between two CRSN nodes varies. The effects of distance between two CRSN nodes on BER are examined under different distances between PU and CRSN node. It is shown that BER sharply increases when distance between PU and CRSN node diminishes. On the other hand, when distance between PU and CRSN node becomes 160 m or more, BER characteristics are almost similar. Therefore, when a PU is closer than 160 m to CRSN node then, BER value is highly related to the distance between PU and CRSN node. Otherwise, the distance between two CRSN nodes severely affects BER value. In

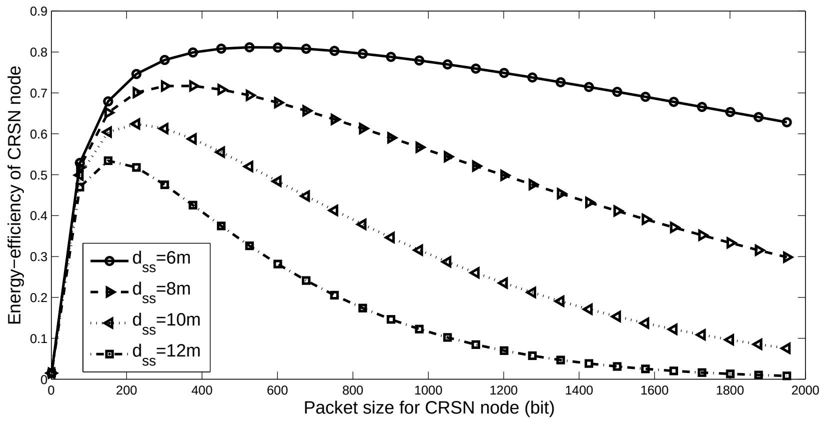

Figure 4.2: Energy-efficiency of CRSN node with varying packet size for different distance between two CRSN nodes.

Figure 4.2, the energy-efficiency of CRSN nodes is shown for varying packet size with different node distance. As expected, energy-efficient packet size sharply increases when the distance between two CRSN nodes diminishes. Conversely, when the distance between two CRSN node increases, it yields extremely high path losses and BER values thereby, high energy-inefficient packet size. Even though dense deployment of CRSN seems advantageous in Figure 4.2, it increases the probability that more than one CRSN nodes coexist on the same channel. When an event occurs, CRSN nodes, which detect the event signal, start searching available channels. If the number of source nodes escalates due to vast deployment, then the probability of coexistence increases. Figure 4.3 points out the impact of the number of source nodes on the energy-efficient packet size. Fixing the total number of the network channels, the behavior of the energy-efficient packet size is investigated for varying number of source nodes. A decrease in the number of source nodes yields an increase in energy-efficient optimal packet size. However, according to (3.14), a certain number of source nodes is required to observe event signal for remaining under the maximum allowed distortion level.

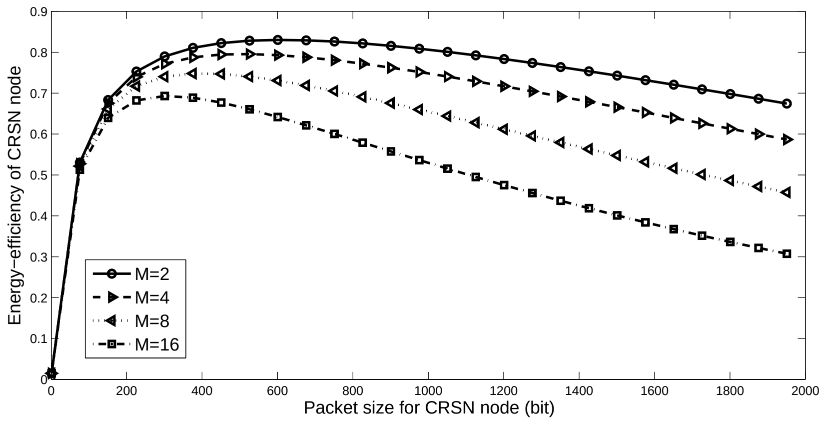

Figure 4.3: Energy-efficiency of CRSN node with varying packet size for different number of source CRSN nodes.

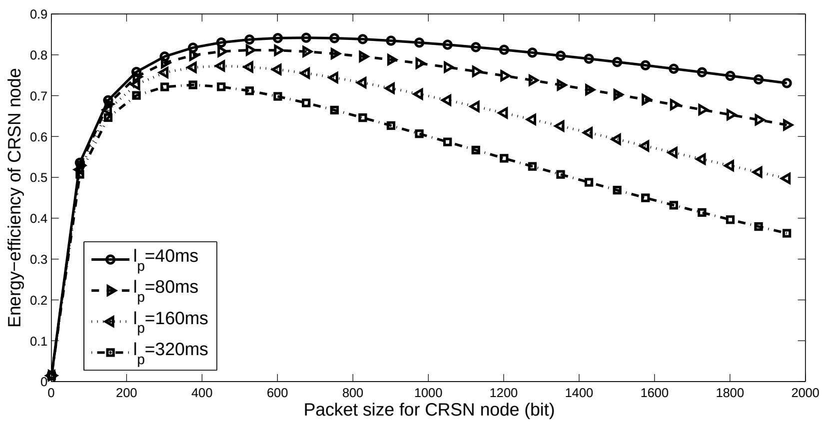

Figure 4.4: Energy-efficiency of CRSN node with varying Packet Size for different average busy time of channel.

In Figure 4.4, energy-efficiency performance for varying packet size under the different average busy time of channel is presented. Figure 4.4 implies that high PU occupancy of channel reduces energy-efficient optimal packet size. CRSN nodes utilize the spectrum in a short interval of time for maintaining acceptable interference level for PU. Moreover, the energy consumption of CRSN node increases due to frequent execution of handoffs.

In Figure 4.5, energy-efficiency performance for varying packet size under the different path-loss exponents is illustrated. Figure 4.5 shows that when path-loss exponent

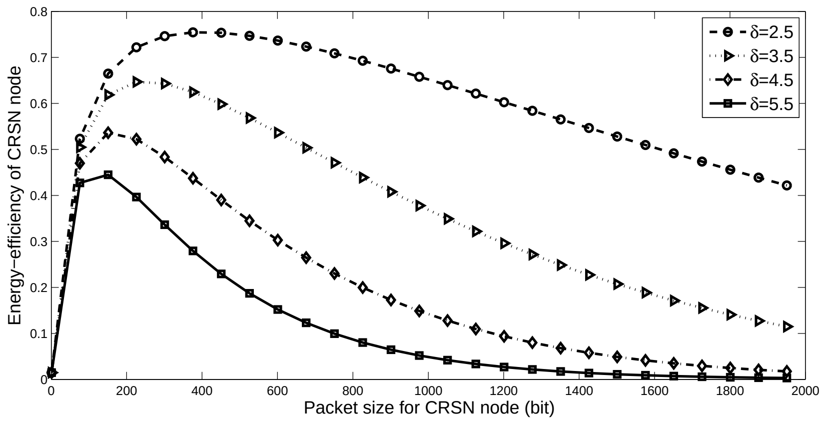

Figure 4.5: Energy-efficiency of CRSN node with varying packet size for different path-loss exponent.

increases energy-efficient optimal packet size sharply decreases. An increase in path-loss exponent increases BER.

4.3 Constraint of Acceptable Interference Level for PU

CRSN operates opportunistically on licensed spectrum band. When the interference that is caused by CRSN communication, exceeds the acceptable level for PU, CRSN communication in the licensed spectrum may be stopped by PU. Therefore, maintaining acceptable interference level for PU is the fundamental concern while operating in the environment for CRSN.

Therefore, we define $\kappa(l_s)$ as the average interference time that PU encounters. In our CRSN model, PU experiences interference in two channel states which are mis-detection and collision states. Therefore, considering (4.16), $\kappa(l_s)$ can be represented as

$$\kappa(l_s) = \frac{l_s}{R(Pr_2 + Pr_5(l_s))}\left[Pr_2(Pr_{on} + Pr_{off}e^{\frac{-l_s}{Rl_p}}) + Pr_5(l_s)Pr_{on}\right] \quad (4.30)$$

It is already mentioned in Section 4.1 definition 3 that the ratio of average interference time over the average transmission time of PU should not exceed I_{max} in order to remain under maximum allowed interference level. Therefore, substituting (4.30) into definition 3, the constraint of acceptable intereference level for PU of CRSN can be formulated as

$$I_{max} \geq \frac{l_s}{Rl_p}[Pr_{on} + \frac{Pr_2 Pr_{off} e^{\frac{-l_s}{Rl_p}}}{Pr_2 + Pr_5}] \tag{4.31}$$

which is further simplified to

$$l_s[Pr_{on} + \frac{Pr_2 Pr_{off} e^{\frac{-l_s}{Rl_p}}}{Pr_2 + Pr_5(l_s)}] - I_{max} Rl_p \leq 0 \tag{4.32}$$

4.4 Constraint of Maximum Distortion Level for Reliable Detection

In this section, we investigate the relation between packet size and distortion level between event signal and its estimation at sink. In Section 3.6, without exceeding the maximum allowed distortion level, selection of the minimum number of source nodes (M^*) is introduced in (3.13) and (3.14). Furthermore, the number of generated bits ($K = 2\tau_s B_s \chi$) for each reading of a source node is given. Hence, the total number of the packets, which should reach the sink node for remaining under distortion level before τ_d finishes, can be formulated as $\frac{M^* K}{l_s - h}$ where h is the packet header. However, the packet losses due to bit errors must be considered when the total number of packets required is calculated. In the worst case, the number of packets transmitted can be calculated as $M^* K \Lambda(l_s)(\frac{l_s}{l_s - h})$. On the other hand, more than one bit error may occur in one packet. However, for the worst case analysis, we assume that a single bit error causes loss of a packet. Therefore, the total number of required packets that must reach sink for reliable detection (ψ) can be determined as

$$\psi(l_s) = \frac{M^* K}{l_s - h}(1 + \Lambda(l_s) l_s) \tag{4.33}$$

Time limitation for one packet to transfer from its source node to the sink is required for calculating $\tau_g(M^*, l_s)$. The number of communication hops, n, is the first parameter to define for the constraint of maximum acceptable distortion level because the time spent at each node is multiplied with the number hops to estimate the total time limit for one packet.

To transmit a packet, CRSN node moves from ready period to sensing period and then goes to decision period. According to sensing results, it may either switch to handoff period or move to transmit period. Hence, total time spendt at each node for transmitting can be estimated as $\tau_n = d + \frac{l_s}{R}$, where d denotes total delay. Since the total number of the required packets is calculated in (4.33), the time interval that starts with event occurence and ends when the last packet, which is generated by source nodes, reaches at the sink can be given as

$$\tau_g(M^*, l_s) = \frac{M^* K n}{l_s - h}\left[(1 + \Lambda(l_s) l_s)\,(d + \frac{l_s}{R})\right] \tag{4.34}$$

Due to densely deployed topology of CRSN node, packets of M^* source nodes can be delivered to sink simultaneously to improve time efficiency. However, in the worst case scenario, to determine $\tau_g(M^*, l_s)$, it is assumed that more than one packet cannot be delivered to the sink at the same time. Therefore, substituting (4.34) instead of $\tau_g(M*, l_s)$, the last constraint of (4.3) can be restated as

$$\frac{\tau_d}{M^* K n} \geq \frac{1 + \Lambda(l_s) l_s}{l_s - h}(d + \frac{l_s}{R}) \tag{4.35}$$

which is further simplified to

$$l_s^2 \Lambda(l_s) + l_s\,(\Lambda(l_s) d R + 1 - c_2 R) + R(d + c_2 h) \leq 0 \tag{4.36}$$

where $c_2 = \frac{\tau_d}{M^* K n}$.

4.5 Packet Size Optimization Problem for CRSN

With respect to (4.12), (4.19), (4.32) and (4.36), energy-efficient packet size optimization problem define in (4.3) can be restated as

$$\begin{aligned} \underset{l_s}{\text{maximize}} \quad & \frac{l_s}{l_s + c_0 R}(1 - \Lambda(l_s))^{l_s} \\ \text{subject to} \quad & l_s[Pr_{on} + \frac{Pr_2 Pr_{off} e^{\frac{-l_s}{R l_p}}}{Pr_2 + Pr_5(l_s)}] - I_{max} R l_p \leq 0, \\ & l_s^2 \Lambda(l_s) + l_s(\Lambda(l_s) d R + 1 - c_2 R) + R(d + c_2 h) \leq 0 \end{aligned} \tag{4.37}$$

where $c_0 = \frac{k_2}{k_1}$.

Figures 4.6 and 4.7 show energy-efficiency of CRSN node for varying packet size. It is represented that (4.32) and (4.36) form the bit interval for determining energy-efficient optimal packet size that enables to maintain acceptable interference level for PU and remain under distortion level between event signal and its estimation. Decision time

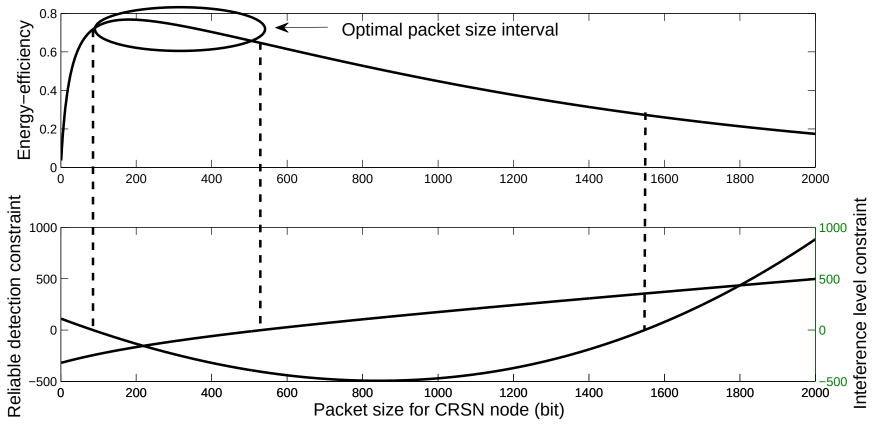

Figure 4.6: Energy-efficiency of CRSN node with acceptable interference level and reliable event detection constraints vs CRSN packet size when $\tau_d = 4s$.

interval (τ_d) is taken as 4 sec. and 3 sec. in Figures 4.6 and 4.7, respectively. 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 (4.32) or (4.36). As can be seen in Figure 4.7, energy-efficiency of CRSN node is around 0.8 when the packet size is approximately 200 bits. However, if this packet size is used in CRSN, the requirement of reliable event detection cannot be satisfied. Therefore, even though usage of 200 bits packet size maximizes energy-efficiency, 250 bits is determined as the energy-efficient optimal packet size in order to meet both requirements of acceptable interference level for PU and reliable event detection at the sink.

In Figure 4.6, 200 bits packet size is in the bit interval that satisfies both constraints of energy-efficient packet size optimization problem. Therefore, energy-efficient optimal packet size is approximately 200 bits in this case.

4.6 Examination of Methods for Solving Optimization Problem

After obtaining energy-efficient packet size optimization problem for CRSN in (4.37), this problem needs to be solved in order to determine closed-form expression for optimal energy-efficient packet size. In [39], similar energy-efficient metric without

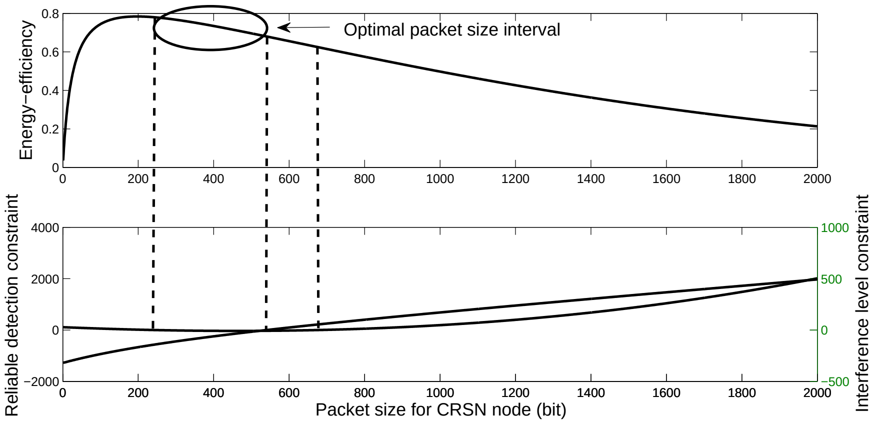

Figure 4.7: Energy-efficiency of CRSN node with acceptable interference level and reliable event detection constraints vs CRSN packet size when $\tau_d = 3s$.

constraints is simply optimized by taking derivative. However, in our work, BER value depends on optimization parameter which increases the complexity of optimization problem while taking derivative. Therefore, in this section, we have investigated some other possible methods in order to solve this optimization problem. Determination of an energy-efficient optimal packet size for CRSN optimization problem can be modeled as a single variable nonlinear constrained optimization problem.

4.6.1 Kuhn-Tucker Condition Method

Lagrange Multipliers is one of the most fundamental method which is used for finding maxima or minima of a function subject to equality constraints. Kuhn-Tucker Conditions (KTC) is expanded method of Lagrange Multipliers including inequality constraints. KTC considers the following problem [35];

$$\begin{aligned} &\textbf{minimize} \quad && f(x) \\ &\textbf{subject to} \quad && g_j(x) \geq 0 \quad \text{for } j = 1, 2, 3, ..., J \\ & && h_k(x) = 0 \quad \text{for } k = 1, 2, 3, ..., K \end{aligned} \tag{4.38}$$

where $x = (x_1, x_2, x_3, ..., x_n)$. With regard to this problem, KTC can be written as

$$\begin{aligned}
&\nabla f(x) - \sum_{j=1}^{J} u_j \nabla g_j(x) - \sum_{k=1}^{K} v_k \nabla h_k(x) = 0 \\
&g_j(x) \geq 0 \quad \text{for } j = 1, 2, 3, ..., J \\
&h_k(x) = 0 \quad \text{for } k = 1, 2, 3, ..., K \\
&u_j g_j(x) = 0 \quad \text{for } j = 1, 2, 3, ..., J \\
&u_j \geq 0 \quad \text{for } j = 1, 2, 3, ..., J
\end{aligned} \tag{4.39}$$

where u_j and v_k are called KTC multipliers. KTC supposes that both objective and constraint functions are differentiable. To apply this method in order to solve our optimization problem in (4.37), we denote

$$\begin{aligned}
f(l_s) &= -\left(\frac{l_s}{l_s + c_0 R}(1 - \Lambda(l_s))^{l_s}\right) \\
g_1(l_s) &= -\left(l_s\left[Pr_{on} + \frac{Pr_2 Pr_{off} e^{\frac{-l_s}{Rl_p}}}{Pr_2 + Pr_5(l_s)}\right] - I_{max} R l_p\right) \\
g_2(l_s) &= -\left(l_s^2 \Lambda(l_s) + l_s\left(\Lambda(l_s) dR + 1 - c_2 R\right) + R(d + c_2 h)\right)
\end{aligned} \tag{4.40}$$

Then, substituting (4.40) into (4.39), we obtain KTC equation set to solve optimization problem. However, the obtained equation set is highly complicated and avoids finding an optimal solution. Therefore, KTC is not a feasible solution method for our optimization problem.

4.6.2 Linearization Method

The linearization method uses the fact that a general nonlinear function $f(x)$ can be approximated in the vicinity of a point x^0 by Taylor's expansion. Consequently, when we ignore the high order terms, $f(x)$ can be expressed as follows

$$f(x) = f(x^0) + \nabla f(x^0)(x - x^0) \tag{4.41}$$

Considering (4.41) and (4.40), our optimization problem at (4.37) turns out to be

$$\begin{aligned}
\underset{x}{\text{minimize}} \quad & f(l_s^0) + \nabla f(l_s^0)(ls - l_s^0) \\
\text{subject to} \quad & g_1(l_s^0) + \nabla g_1(l_s^0)(l_s - l_s^0) \geq 0 \\
& g_2(l_s^0) + \nabla g_2(l_s^0)(l_s - l_s^0) \geq 0
\end{aligned} \tag{4.42}$$

Although, (4.42) simplifies energy-efficient packet size optimization problem, numerical analysis shows that the values of linearized equations do not match with values of the actual non-linear equations. Therefore, solving our optimization problem by applying linearization method yields unfeasible energy-efficient optimal packet sizes.

4.6.3 Sequential Quadratic Programming (SQP) Method

Sequential quadratic programming (SQP) is one of the most popular methods to solve single variable nonlinear constrained optimization problems. The algorithm of this method can be summarized as [35]

1. Determine initial estimation value (x^0)
2. Formulate the Quadratic Programming problem

$$\begin{aligned} \text{minimize} \quad & \nabla f(x^{(t)})d + \frac{1}{2}\nabla^2 f(x^{(t)})d^2 \\ \text{subject to} \quad & h_k(x^{(t)}) + \nabla h_k(x^{(t)})d = 0 \quad \text{for } k = 1, 2, 3, ..., K \\ & g_j(x^{(t)}) + \nabla g_j(x^{(t)})d \geq 0 \quad \text{for } j = 1, 2, 3, ..., J \end{aligned} \tag{4.43}$$

3. Solve the problem for d and set $x^{(t+1)} = x^{(t)} + d$
4. Check for convergence. If not converged, repeat step 1.

SQP assumes that the objective function is at least twice differentiable. Hence, the application of SQP to our optimization problem in (4.37) yields the following:

1. Determine the initial estimation value (l_s^0)
2. Formulate the Quadratic Programming problem

$$\begin{aligned} \underset{l_s}{\text{minimize}} \quad & \nabla f(l_s^{(t)})d + \frac{1}{2}\nabla^2 f(l_s^{(t)})d^2 \\ \text{subject to} \quad & g_1(l_s^{(t)}) + \nabla g_1(l_s^{(t)})d \geq 0 \\ & g_2(l_s^{(t)}) + \nabla g_2(l_s^{(t)})d \geq 0 \end{aligned} \tag{4.44}$$

3. Solve the problem for d and set $l_s^{(t+1),} = l_s^{(t)} + d$
4. Check for convergence. If not converged, repeat step 1.

When the iteration number increases, the calculation of the optimal packet size becomes significantly difficult. To address this challenge, the SQP algorithm of MATLAB optimization toolbox is used. We check the results of SQP algorithm with graphical results that are obtained in Figures 4.6, 4.7 and observe that the results of SQP algorithm of MATLAB optimization toolbox is accurate. Hence, SQP method is adopted in order to solve energy-efficient packet size optimization problem.

CHAPTER 5

NUMERICAL ANALYSIS OF ENERGY-EFFICIENT OPTIMAL PACKET SIZE

In this chapter, the variation of optimal packet size with respect to different parameters of CRSN is observed through numerical analysis. We use SQP algorithm in MATLAB optimization toolbox in order to obtain energy-efficient optimal packet size results. The variation of energy-efficient optimal packet size is investigated with respect to number of channels and source nodes, different data rates, the total amount of required data, sensing time, event signal bandwidth and different PU activity patterns.

To obtain closed-form expressions, energy-efficient packet sizes are illustrated in 3D plots with respect to the variation of two important parameters of optimization problem in (4.37). The results are shown in Figures 5.5, 5.7, 5.9, 5.11 and 5.13. Each data point on these plots represents a single solution of the SQP algorithm in MATLAB optimization toolbox. Surface fitting of the data points is overlaid on each plot in Figures 5.6, 5.8, 5.10, 5.12 and 5.14. According to the results of surface fitting, closed-form expression for optimal packet size is obtained with respect to varying parameters.

There are many parameters affecting the optimal packet size. The parameters used in the analysis are summarized in table 5.1. Commercially available wireless sensor node knowledge is used for theoretically estimating energy consumption of CRSN node in cognitive cycle and sleep states [32], [40], [41].

Table 5.1: 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 ratio	0.1
d_{ss}	CRSN nodes distance	8 m
d_{sp}	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	2
Pr_{on}	PU occupancy probability	$\frac{1}{3}$
λ	threshold value	5 dB

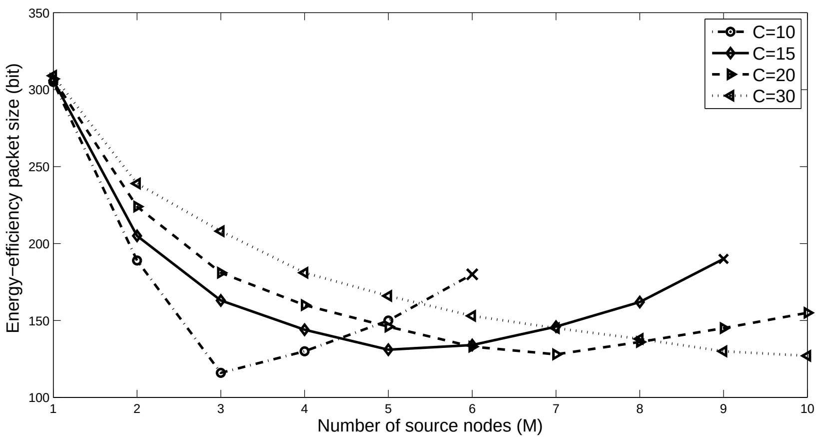

Figure 5.1: Variation of energy-efficient packet size vs. number of source node under different number of channels.

5.1 Effect of network channels and source nodes number

In this section, we evaluate the effects of number of network channels and source nodes. Variation of energy-efficient optimal packet size with respect to different number of source nodes under different number of channels is given in Figure 5.1. It is observed that when the number of channels increases, energy-efficient packet size increases as the probability of coexistence on the same channel decreases. On the other hand, an increase in the number source nodes yields a decrease in energy-efficient optimal packet size. The main reason of this effect is 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 to determine optimal packet size and increases the optimal packet size from 100 bits to 200 bits for these cases. On the other hand, it can be seen that for $C = 20$, $C = 30$, energy-efficient optimal packet size decreases with increasing the number of the source nodes. Moreover, in the cases of $C = 10$, $M \geq 7$ and $C = 15$, $M \geq 9$, energy-efficient optimal packet size cannot be calculated due to the increase of BER caused by channel scarcity and also an increase in the total amount of generated data. Note that the points on the curves in Figure 5.1 marked with x represent the last feasible solution of energy-efficient packet size optimization problem for $C = 10$, $C = 15$.

5.2 Effect of total data load and data rate

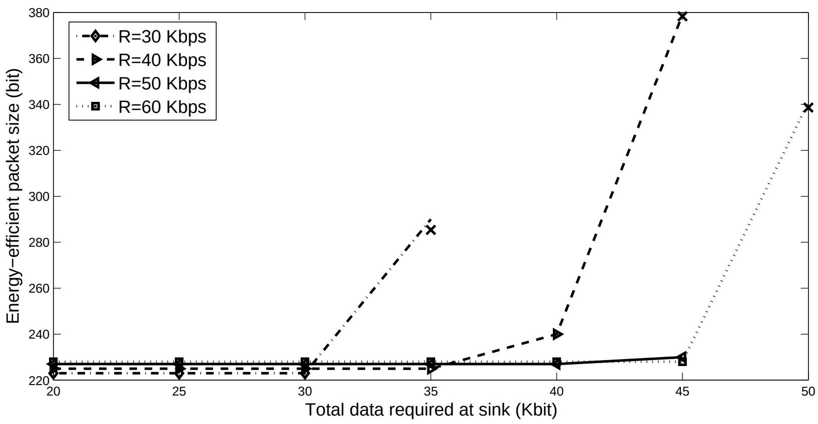

Figure 5.2: Variation of energy-efficient packet size vs. total data required at sink with different data rates.

In Figure 5.2, the effect of generated total amount of data load on the detection and estimation of the event signal is investigated with different data rates of CRSN node. It can be seen that data rate of 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 total amount of 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 Figure 5.2 marked with x represent the last feasible solution of energy-efficient packet size optimization problem for $R = 30$, $R = 40$ and $R = 60$. As an example, for $R = 30$ Kbps, when the total amount of data exceeds 35 Kbit, energy-efficient packet size cannot be found.

5.3 Effect of sensing time and PU activity patterns

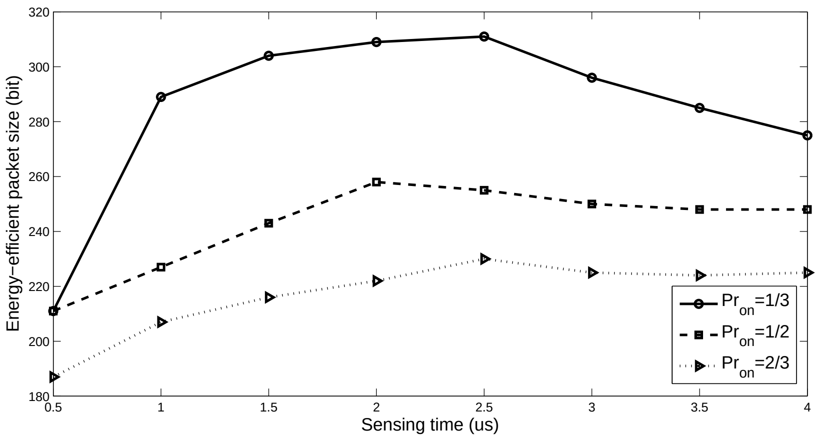

Figure 5.3: Variation of energy-efficient packet size vs. sensing time with different PU behavior.

The effect of sensing time under different PU behaviors is shown in Figure 5.3. Clearly, the PU activity on the channel limits the optimal packet size. When PU occupancy on channel increases, CRSN nodes are forced to communicate in a short time interval that reduces optimal packet size. As can be seen in Figure 5.3, for $Pr_{on} = 1/3$ energy-efficient optimal packet size takes values up to 310 bits. On the other hand, for $Pr_{on} = 2/3$, the maximum value of energy-efficient optimal packet size is 220 bits. Furthermore, it is shown that the increase in sensing period amplifies the probability of channel false alarm state, which, in turn, reduces the probability that the channel is in success state. Hence, when $t_s \geq 2.5\ \mu s$, an increase in sensing time reduces optimal packet size.

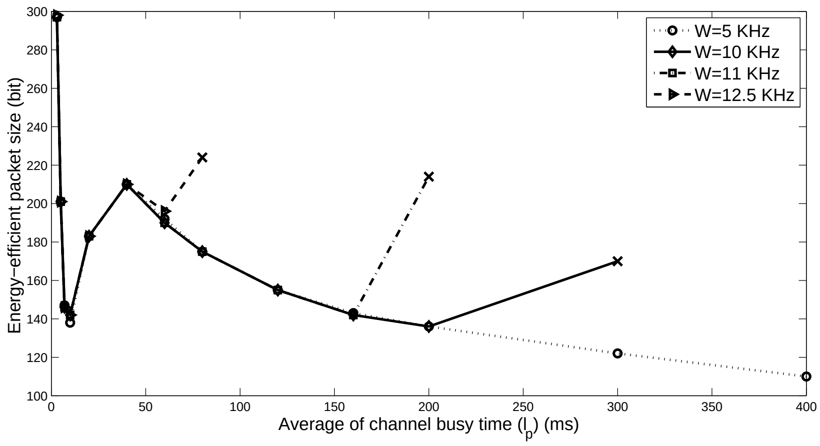

Figure 5.4: Variation of energy-efficient packet size vs. average of channel busy time with different event signal bandwidth when v_p=80 ms.

5.4 Effect of event signal bandwidth and channel busy time

In Figure 5.4, the effect of channel busy time under varying event signal bandwidth is analyzed. When event signal bandwidth becomes higher, it leads to 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 in order 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 Figure 5.4 marked with x represent the last feasible solution of energy-efficient packet size optimization problem for $W = 10$, $W = 11$ and $W = 12.5$. For $W = 5$ KHz, CRSN can transfer the total amount data load to the sink while varying l_p from 20 ms to 400 ms and energy-efficient optimal packet size decreases from 210 bits to 100 bits with the increasing l_p.

5.5 Closed-form expressions for energy-efficient optimal packet size

To proceed further, we focus on closed-form expression of energy-efficient optimal packet size. Different realistic CRSN scenarios are formed based on the realization of CRSN. With the help of the MATLAB surface fitting toolbox, 3D plots of the energy-efficient packet sizes are fitted to quadratic equation surfaces. As a result, matched closed-form optimal packet size expression for each scenario is obtained. Furthermore, the error margin between the real values and the matched equation results are obtained.

5.5.1 Effect of data rate and energy consumption of CRSN node

Scenario 1: PU behavior, average distance between PU and CRSN nodes, number of communication hops in the network, sampling and decision times are assumed to be known. The number of source nodes is also decided. The unknown parameters for this scenario are energy consumption and communication data rate of CRSN node.

In Figure 5.5, the effects of c_0 and R are illustrated under different noise variations where $c_0 = \frac{k_2}{k_1}$ and is defined as energy consumption parameter of CRSN node. It can be seen that increasing σ_n from 0.5 to 2 results in 30% decrease in energy-efficient optimal packet size for this scenario. Additionaly, energy-efficient optimal packet size increases with increasing c_0 and takes values up to 650 bits when $c_0 = 0.01$. However, increasing c_0 hampers the energy-efficiency of CRSN node. Hence, increasing the energy that is consumed in cognitive cycle periods before the actual transmission, increases the energy-efficent optimal packet size and decreases the energy-efficiency of CRSN node. On the other hand, variation of data rate of CRSN node does not have significant effect on the optimal packet size.

The variation of energy-efficient packet sizes for varying c_0 and R in Figure 5.5 is fitted to quadratic equation surface in Figure 5.6 with the help of the MATLAB surface fitting toolbox. Thus, the closed-form expression for this scenario can be given as

$$l_s(c_0, R) = 218.7 + 89630c_0 - 0.8857R - 8241x10^3c_0^2 + 405.3c_0R - 0.00219R^2 \quad (5.1)$$

where $c_0 = \frac{k_2}{k_1}$. Then, average error margin is calculated with respect to (5.1) and can be given as 1,18%.

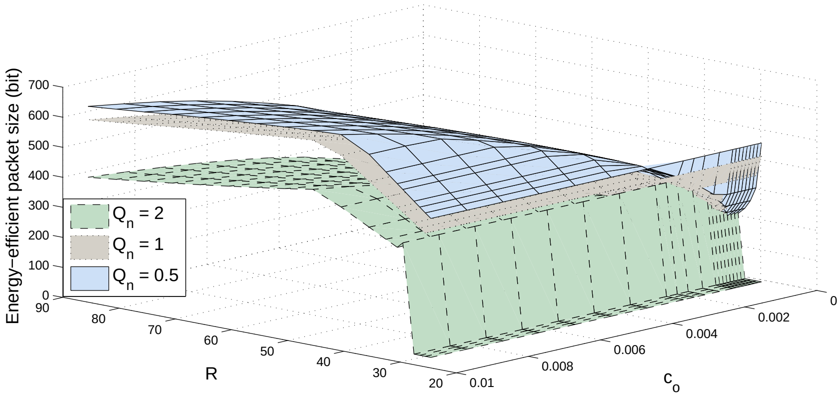

Figure 5.5: Variation of energy-efficient packet size with respect to data rate and energy consumption of CRSN node under different noise variance.

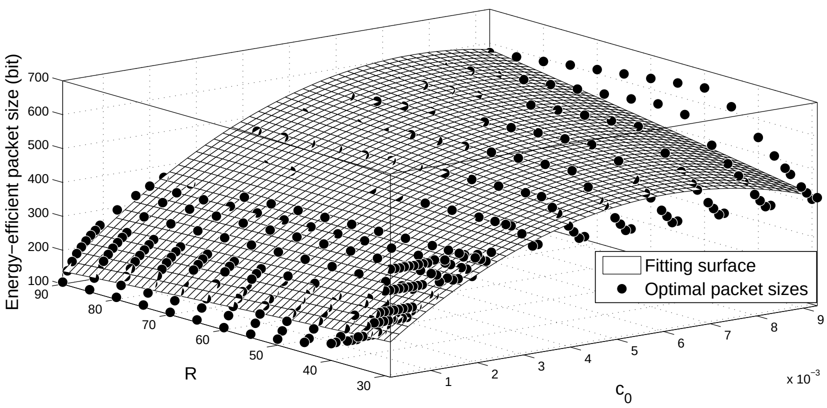

Figure 5.6: Energy-efficient packet sizes and optimal packet size fitting surface vs c_0 and R.

5.5.2 Effect of BER and energy consumption

Scenario 2: Energy consumption of CRSN node, distance between CRSN nodes and output powers are unknown parameters for this scenario. On the other hand, number of source nodes in the network, PU behavior, number of communication hops, sample and decision times can be estimated.

In Figure 5.7, the variation of energy-efficient packet size is illustrated with varying c_0 and c_1 where $c_1 = \Lambda_I - \Lambda_S$ and is defined as BER parameter. It is once again shown that an increase in c_0 increases the energy-efficient optimal packet size. On the other hand, when c_1 increases from 0.001 to 0.01, energy-efficient packet size sharply decreases from 600 bits to 250 bits for $\sigma_n = 0.5$, from 500 bits to 200 bits for $\sigma_n = 1$ and from 400 bits to 100 bits for $\sigma_n = 2$. Therefore, it can be observed that c_1 parameter dominates the calculation of the optimal packet size in comparison to c_0 parameter. Hence, for this scenario, results reveal that BER is more important than the energy consumption of CRSN node for determining energy-efficient optimal packet size for CRSN.

The variation of energy-efficient packet size for varying c_0 and c_1 in Figure 5.7 is fitted to quadratic equation surface in Figure 5.8 with the help of the MATLAB surface fitting toolbox. Thus, the closed-form expression for this scenario can be given as

$$l_s(c_0, c_1) = 363.1 + 1133x10^2 c_0 - 67430c_1 - 5551x10^3 c_0^2 - 5039x10^3 c_0 c_1 + 4834x10^3 c_1^2 \quad (5.2)$$

where $c_1 = \Lambda_I - \Lambda_S$ and $c_0 = \frac{k_2}{k_1}$. Then, average error margin is calculated with respect to (5.2) and can be given as 2.79%.

5.5.3 Effect of BER and reliable event detection constraint

Scenario 3: Energy consumption of CRSN node, and communication data rate and PU behavior can be estimated. Unknown parameters are BER, number of communication hops and source nodes, sample and decision times for this scenario.

In Figure 5.9, the variation of energy-efficient packet size is illustrated for varying c_1 and c_2 where $c_2 = \frac{\tau_d}{M^* Kn}$ and is defined as reliable event detection parameter.

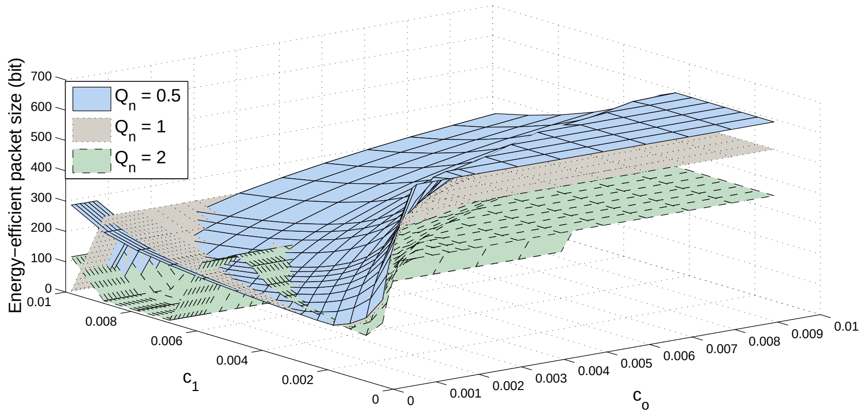

Figure 5.7: Variation of energy-efficient packet size with respect to BER and energy consumptions of CRSN node under different noise variance.

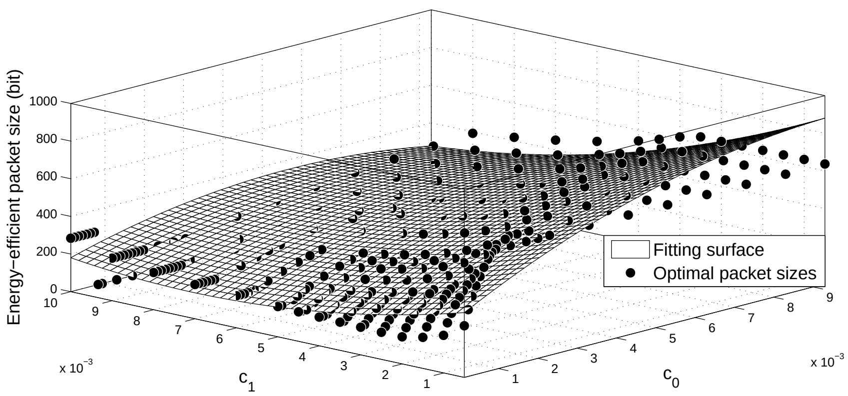

Figure 5.8: Energy-efficient packet sizes and optimal packet size fitting surface vs c_0 and c_1.

The significant effect of c_1 is once again observed in the results. It is observed that increasing c_1 from 0.001 to 0.01, energy-efficient packet size varies from 600 bits to 100 bits with respect to noise variance on the channel. On the other hand, when $c_2 \leq 5 \times 10^{-5}$, the requirement of reliable event detection becomes dominant parameter in determining the energy-efficient optimal packet size. First, this requirement increases energy-efficient packet size up to 300 bits in order to transfer the total data required at sink. Then, as c_2 keeps decreasing from 5×10^{-5}, it cannot be satisfied with any value of packet size, and hence, optimal packet size cannot be found.

The variation of energy-efficient packet sizes with varying c_1 and c_2 in Figure 5.9 is fitted to quadratic equation surface in Figure 5.10 with the help of the MATLAB surface fitting toolbox. Thus, the closed-form expression for this scenario can be given as

$$l_s(c_1, c_2) = 546.9 - 1445x10^2c_1 + 183x10^6c_1c_2 + 1462x10^4c_1^2 - 492210^3c_1c_2 \quad (5.3)$$

where $c_2 = \frac{\tau_d}{M^*Kn}$ and $c_1 = \Lambda_I - \Lambda_S$. Then, average error margin is calculated with respect to (5.3) and can be given as 2,93%.

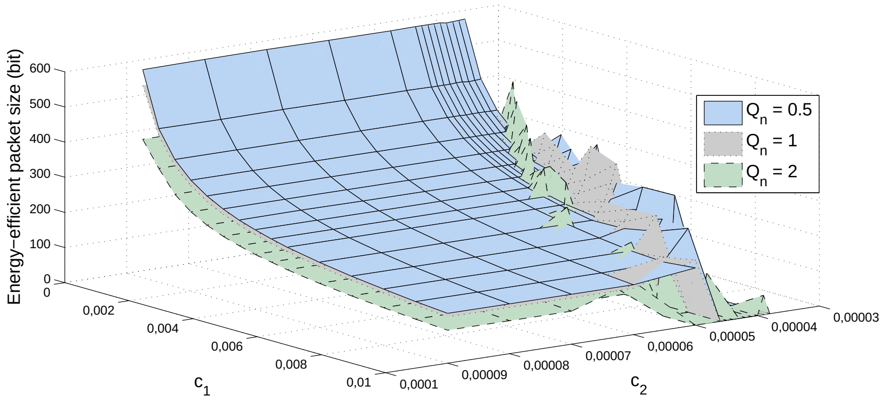

Figure 5.9: Variation of energy-efficient packet size with respect to BER and reliable event detection constraint under different noise variance.

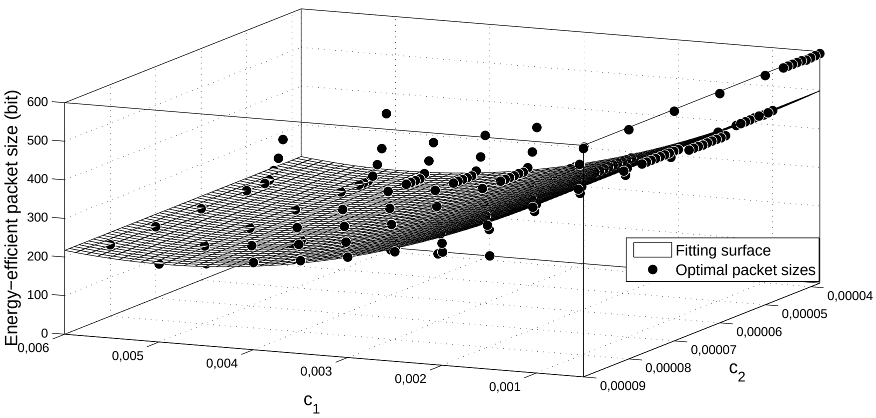

Figure 5.10: Energy-efficient packet sizes and optimal packet size fitting surface vs c_1 and c_2.

5.5.4 Effect of BER and PU behavior

Scenario 4: Energy consumption, communication data rate, number of source nodes and communication hops can be determined. However, PU behavior and BER cannot be estimated for this scenario.

The parameters of c_1 and l_p are varied and obtained energy-efficient packet size results are demonstrated in Figure 5.11. It is shown that increase in both c_1 and l_p yields sharp decrease in energy-efficient packet size. While increasing l_p from 50 ms to 350 ms, and increasing c_1 from 0.001 to 0.01, energy-efficient packet size decreases 600 bits to 100 bits. For $\sigma_n = 2$ when $c_1 \geq 0.04$ and $l_p \geq 50$ ms, for $\sigma_n = 1$ when $c_1 \geq 0.06$ and $l_p \geq 75$ ms and for $\sigma_n = 0.5$, when $c_1 \geq 0.08$ and $l_p \geq 100$ ms, energy-efficient packet size cannot be determined due to the high occupancy of PU and an increase in BER. On the other hand, as in mentioned in Section 5.4, when $l_p \leq 50$ ms, the requirement of acceptable level of interference for PU becomes dominant parameter and determines energy-efficient optimal packet size.

The variation of energy-efficient packet sizes for varying l_p and c_1 in Figure 5.11 is fitted to quadratic equation surface in Figure 5.12 with the help of the MATLAB surface fitting toolbox. Thus, the closed-form expression for this scenario can be given as

$$\begin{aligned} l_s(c_1, l_p) \quad = \quad & 593.3 - 2188x10^2 c_1 + 304.8 l_p + 7529x10^4 c_1^2 - 1006x10^3 c_1 l_p - 1113 l_p^2 - \\ & 1001x10^7 c_1^3 + 1378x10^5 c_1^2 l_p + 1633x10^3 c_1 l_p^2 - 665.4 l_p^3 \end{aligned} \tag{5.4}$$

where $c_1 = \Lambda_I - \Lambda_S$. Then, average error margin is calculated with respect to (5.4) and can be given as 2,73%.

5.5.5 Effect of BER and probability of coexistence

Scenario 5: BER, number of source nodes and channels are unknown parameters. On the other hand, energy consumptions and data rate of CRSN node, communication hops, decision and sampling times can be estimated.

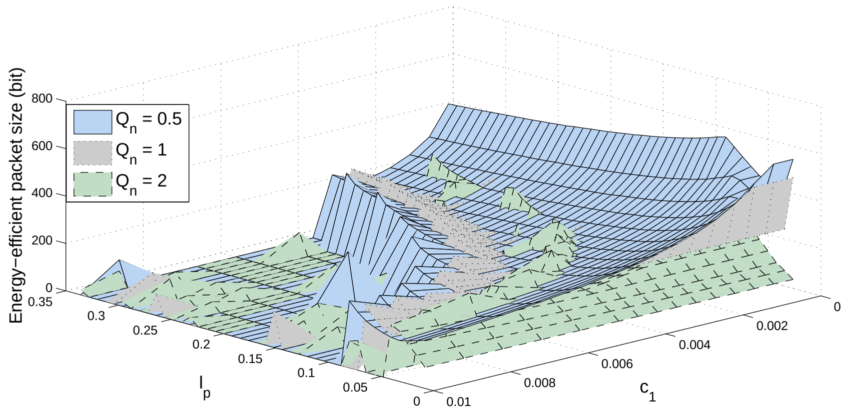

Figure 5.11: Variation of energy-efficient packet size with respect to BER and PU behavior under different noise variance.

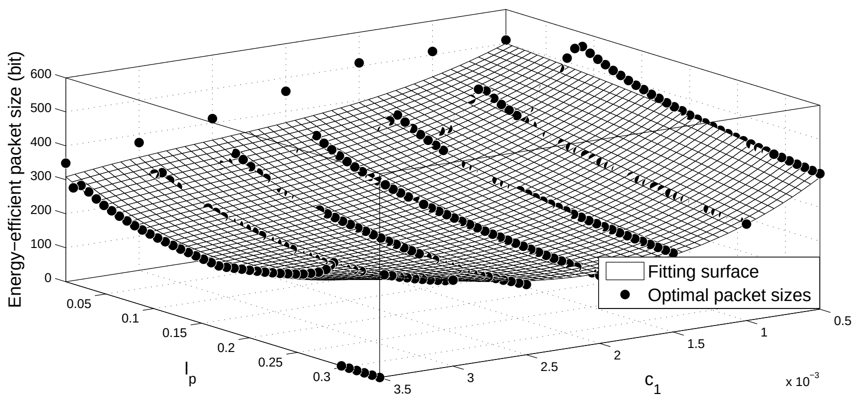

Figure 5.12: Energy-efficient packet sizes and optimal packet size fitting surface vs c_1 and l_p.

In Figure 5.13, the variation of the optimal packet size for varying Pr_4 and c_1 is shown. An increase in probability of coexistence reduces the probability that the channel is in success state, and hence, the energy-efficient optimal packet size. While moving Pr_4 from 0.05 to 0.3, energy-efficient packet size decreases from 652 bits to 286 bits when $\sigma_n = 0.5$, from 560 bits to 227 bits when $\sigma_n = 1$, from 400 bits to 180 bits when $\sigma_n = 2$. It is shown that when $Pr_4 \geq 0.1$ and $c_1 \geq 0.004$, retransmission of packets increases due to packet losses caused by bit errors and CRSN cannot transfer required data to sink in a decision time. Hence, an increase in both parameters sharply decreases in

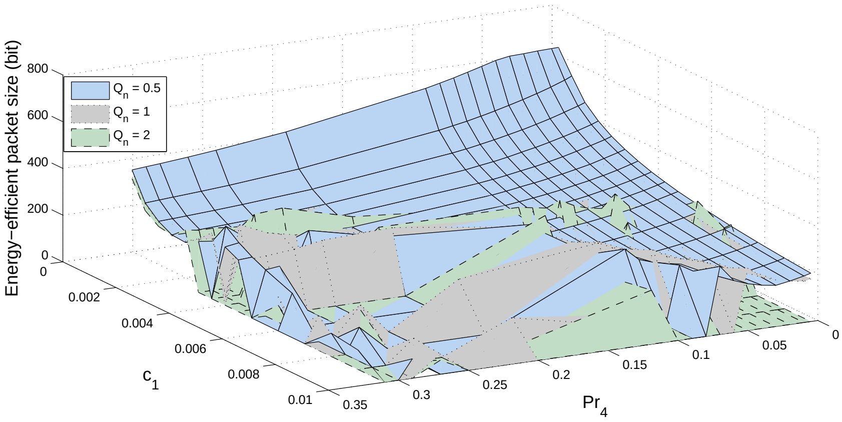

Figure 5.13: Variation of energy-efficient packet size with respect to BER and probability of coexistence under different noise variance.

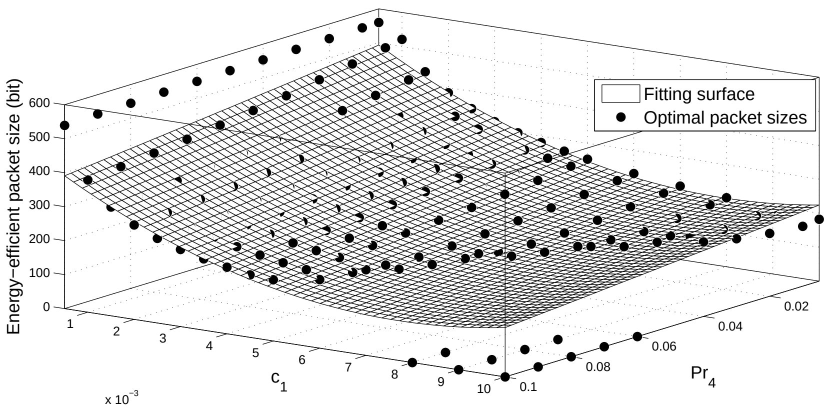

Figure 5.14: Energy-efficient packet sizes and optimal packet size fitting surface vs c_1 and Pr_4.

the energy-efficient optimal packet size.

The variation of energy-efficient packet sizes for varying c_1 and Pr_4 in Figure 5.13 is fitted to quadratic equation surface in Figure 5.14 with the help of the MATLAB surface fitting toolbox. Thus, the closed-form expression for this scenario can be given as

$$\begin{aligned} l_s(c_1, Pr_4) &= 539.9 - 84140c_1 - 1152Pr_4 + 53x10^5 c_1^2 \\ &\quad +26410c_1 Pr_4 + 562.4Pr_4^2 \end{aligned} \tag{5.5}$$

where $c_1 = \Lambda_I - \Lambda_S$. Then, average error margin is calculated with respect to (5.5) and can be given as 1,71%.

CHAPTER 6

CONCLUSION

Cognitive Radio Sensor Networks (CRSN) is introduced as a promising solution to address the unique challenges of Wireless Sensor Networks (WSN) which have been widely used for reliable event detection for many applications. However, there exist many open research issues for the realization of CRSN. In this thesis, 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.

For this purpose, firstly, we structured CRSN architecture based on the existing studies on both sensor and CR networks. Design issues of PU behavior, spectrum sensing, dynamic spectrum access, and channel states are analyzed in detail. We investigate the fact that, for CRSN node, BER of channel is dependent on its own packet size. Furthermore, PU behavior on channel affects the energy consumption of CRSN node. Then, energy-efficient packet size optimization problem is analytically formulated based on the proposed CRSN architecture.

Secondly, we investigate several methods in order to solve optimization problem. SQP method is used to determine energy-efficient optimal packet size. Then, variation of optimal packet size is analyzed with respect to number of source nodes, total required data load, sensing time and different PU activity patterns. Hence, it is emphasized that determining energy-efficient packet size requires accurate calculations. In some cases energy-efficient packet size cannot be exist because the constraints of optimization problem cannot be satisfied with any packet size. Lastly, we define closed-form expression of energy-efficient optimal packet size for different realistic CRSN scenarios.

With the help of the MATLAB surface fitting toolbox, 3D plots of the energy-efficient packet sizes are fitted to quadratic equation surfaces. Furthermore, the error margin between the real values and the matched equation results are calculated.

Results reveal that determination of energy-efficient packet size depends on the many parameters of CRSN. Among the others, we observe 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.

It is also observed that there is a tradeoff between remaining under the maximum allowed distortion level and the total amount of data load in network. Increasing the number of source nodes reduces distortion between event signal and its estimation at the sink and increases the total number of packets which are injected to network. In Figures 5.1 and 5.2, it is illustrated that increasing the number of the source nodes and the total amount of data load may yield unfeasible solutions for energy-efficient packet size optimization problem. Therefore, the number of source nodes is one of the critical parameters for determining energy-efficient packet size.

We emphasize that energy-efficient packet size does not significantly change with the variation of data rate of CRSN node. Increasing R from 20000 kbps to 90000 kbps does not affect the energy-efficient packet size. On the other hand, R determines the maximum total amount of data load that can be transferred to the sink node in a decision time interval.

We present that there is an optimal sensing time interval of energy detector in order to set accurate channel state probabilities and hence, determine energy-efficient packet size. Optimal sensing duration is determined as 2 μs for our energy-efficient packet size optimization problem.

In Figures 5.5, 5.7, 5.9, 5.11 and 5.13, variation of energy-efficient packet size is investigated under different noise variations. We observe that increasing σ_n from 0.5 to 2 results in 30% decrease in energy-efficient packet size.

Our work provides a better understanding of designing packet size for CRSN and its limitations. In this study, we do not consider any error correction method. It is assumed that one bit error causes a packet loss. However, application of error correction algorithms may increase energy-efficiency. Hence, as a future work, application of error correction methods can be studied.

In optimization problem, fixed packet size is used instead of adaptive packet size due to synchronization between CRSN nodes. However, our optimization strategy can be used for adaptive packet size. Hence, the effect of adaptive packet size to energy-efficiency can be evaluated.

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