Performance Analysis and Channel Resource Management in Cognitive Radio Sensor Networks

PERFORMANCE ANALYSIS AND CHANNEL RESOURCE MANAGEMENT IN COGNITIVE RADIO SENSOR NETWORKS

BY

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This thesis is dedicated to my father, my mother and Rui Yang.

Abstract

Building a wireless sensor network (WSN) based on cognitive radio can be promising in the near future in order to provide data transmissions with quality of service requirements, while avoiding the interference in the license-free spectrum and high cost in accessing dedicated spectrum.

In this thesis, we design a cognitive radio sensor network (CRSN) that integrates wireless sensor networking and cognitive radio technology, and analyze its performance. The network opportunistically accesses vacant channels in the licensed spectrum. When the current channel becomes unavailable, the devices switch to another available channel. The network supports both real-time and non-real-time traffic. Delay performance for the real-time traffic and throughput for the non-real-time traffic are studied. Two types of the real-time traffic are considered: bursty traffic where a burst of packets are generated periodically and each burst includes a random number of packets, and Poisson traffic where packet arrivals follow a Poisson process. Analytical models are developed for the average packet transmission delay when supporting each type of the real-time traffic, and simulation results of both the average transmission delay and packet drop rate performance are demonstrated. Our results indicate that real-time traffic can be effectively supported in the CRSN. Given the total number of candidate channels that can possibly be used by a CRSN, we consider

how to allocate the channels among different clusters in order to maximize the system throughput. A heuristic scheme is designed to find the optimum channel allocations that achieves the same throughput as the exhaustive search method.

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List of Abbreviations

WSN Wireless Sensor Network

CR Cognitive Radio

CRSN Cognitive Radio Sensor Network

WPAN Wireless Personal Area Network

BS Base Station

CPE Customer Premises Equipment

MAC Medium Access Control

FCC Federal Communication Committee

WRAN Wireless Regional Area Network

WLAN Wireless Local Area Network

QoS Quality of Service

CH Cluster Head

CBR Constant Bit Rate

BE Best Effort

SF Superframe

GTS Guaranteed Time Slot

CAP Contention Access Period

PST Packet Service Time

CAI Channel Available Interval

CUI Channel Unavailable Interval

COI Channel Outage Interval

RI Renewal Interval

TCAI Truncated Channel Available Interval

TCOI Truncated Channel Outage Interval

NCAI Non-truncated Channel Available Interval

NCOI Non-truncated Channel Outage Interval

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Chapter 1

Introduction and Background

This chapter includes a general overview of wireless sensor networks (WSNs) and cognitive radio networks (CRNs), followed by the motivations to integrate the two technologies.

1.1 Background

1.1.1 Wireless Sensor Networks

General Concepts and Applications

A WSN is a set of small autonomous sensing devices (called sensor nodes or motes sometimes) that are distributed in an area or object for the purpose of monitoring various physical or environmental parameters, including temperature, sound, chemicals, vibration, pressure and motion, in a cooperative manner [1].

The motivation in early times for building WSNs was military tasks such as anti-submarine sound surveillance systems [2]. Nowadays, applications of WSNs appear in almost every aspect of our daily lives, such as medical care, fire monitoring, chemical emission monitoring, industrial surveillance and wild animal research. Future usage of WSNs may include, but is not limited to, wearable computing [3] devices that can monitor vital functions and report them to the doctor, home automation sensors that monitor temperature, humidity and ventilation and control an air conditioner system according to information provided by the sensors, and a sensor network that detects changes in the structural integrity of buildings or bridges.

Hardware Components

A practical sensing device usually consists of the following basic components: sensor, antenna and transceiver, battery/external power interface, microprocessor unit, memory unit and sometimes programming interface. Since 1990s, technology advances in the micro-electronic area have enabled production of smaller processors, memories and transceivers, which reduce the size of the sensing devices. Recent researches on embedded system and system-on-a-chip (SoC) even integrate microprocessor, AD/DA converter and memory on a single chip. In the mean time, the computing power of such devices has been growing exponentially since the frequency of processor and storage size of memory per unit square are largely increased.

Popular Protocols

There are currently several standards widely accepted or under development for WSNs. Major standards and standardization groups include IEEE 802.15.4 [4], IEEE 1451 [5] and IEC 62591 [6], among which IEEE 802.15.4 is the most popular one. IEEE 802.15.4-2006 has specified the lower two layers, physical layer and MAC layer, for low rate-wireless personal area networks (LR-WPANs). It aims at providing wireless personal area networks (WPANs) with low-cost, low-speed ubiquitous communications between devices. There are several specifications derived from IEEE 802.15.4-2006: *6LoWPAN* [7], ISA 100 [8], *WirelessHART* [9][10], and *ZigBee* [11].

WSNs based on the IEEE 802.15.4 [4] standard operate on one of the three possible unlicensed frequency bands: 868.0-868.6 MHz in Europe, 902-928 MHz in North America, and 2400-2483.5 MHz worldwide. As a result, WSNs working under IEEE 802.15.4 are expected to suffer from heavy interference caused by other networks sharing the same spectrum. On the other hand, assigning an exclusive licensed band to WSNs is not practical, given their low data rates, relatively small coverage, and the currently precious spectrum resources. As a result, the ability of providing both reliable and efficient data communications in such networks is still in doubt.

1.1.2 Cognitive Radio Technology

Limitations of Static Spectrum Allocation

According to a survey from Federal Communication Committee (FCC) report [12], most radio bands in the United States have already been allocated to certain licensees. However, most of the assigned radio frequencies are inefficiently utilized. For example, the frequency bands for cellular networks are overloaded in most areas, but for the amateur radio and paging are not. Studies have shown that the spectrum utilization depends strongly on time and space [13]: some frequency bands are only occupied for a very small portion of time in a certain time period, some other frequency bands are only occupied partially, and the rest of the frequency bands are heavily loaded. The fixed spectrum allocation prevents rarely utilized bands from being used by unlicensed users, even when their transmissions would not interfere with the licensed service.

Concepts of Cognitive Radio Technology

Based on this situation, the term of *spectrum holes* is introduced: *A spectrum hole is a band licensed to a licensee (Primary User, or PU), yet at a certain point, in terms of time or space, is not being utilized by the licensee.* Spectrum utilization can be significantly improved if secondary users (not being licensed) can correctly access a spectrum hole without interfering with the licensees.

Motivated by the idea described above, Cognitive Radio (CR) [14][15] is the technique that focuses on solving the contradiction between increasing wireless applications and exhausted spectrum resources [16][17]. The idea of cognitive radio was first presented officially by Joseph Mitola III in [14].

Cognitive radio is built on (but not limited to) the technical basis of software-defined radio (SDR), where components are implemented using software on personal computers or embedded computing devices and thus are reconfigurable. The concept of cognitive radio has further extended SDR. Cognitive radio is designed to be a fully reconfigurable intelligent wireless communication system that can automatically acquire and analyze information from the environment, and adjust certain operating parameters in real-time to adapt to the environment change or to fulfill the requirement of the network and/or users [13]. Characterized by the ability of exploring and utilizing spectrum opportunities, cognitive radio has a potential to be used in special-purposed regional networks, for example, sensor networks. A cognitive radio network (CRN) is able to identify and exploit local and instantaneous spectrum availability while limiting interference to primary users (licensees), and thus communicate with both reliability and efficiency.

The Full Cognitive Radio ("Mitola Radio") concept should take consideration of every possible parameter in a wireless network. However, in research and practice, the concept of cognitive radio is usually narrowed down to spectrum sensing cognitive radio (SSCR), where only adjustable radio frequency is considered, since spectrum sensing (particularly in the TV bands) is the major issue in cognitive radio at the moment. The core issues of SSCR are in high quality spectrum sensing devices and algorithms for sharing spectrum sensing data between sensors.

Standard

IEEE 802.22 is the first standardization progress for cognitive radio [18]. It allows wireless regional area network (WRAN) to share spatially unutilized spectrum assigned to Television Broadcast Service (UHF/VHF between 54 MHz and 862 MHz), as long as no interference incurred, to provide broadband access to rural environments, where population density is low and wired broadband is economically infeasible. The standard finalization was expected to be in the first quarter of 2010 (draft 3.0 is available now on the official web site of the working group but still no news of finalization).

In the standard, IEEE and FCC intend to form a centralized approach for spectrum opportunity discovery. The WRAN consists of base stations (BSs) and customer premises equipment (CPE), and operates in a point to multipoint (star topology) manner. The BS controls the medium access for all CPEs associated with it via wireless links. It is equipped with GPS in order to consult the central servers (managed by FCC) for available channels in its located area. Alternative proposals allow the BS to perform local spectrum sensing and decide by itself which channel is available. In order to obtain higher bandwidth and provide high speed connections in long distance, channel bonding is introduced so that more than one channel are used simultaneously for transmitting or receiving.

To strictly avoid interference and to minimize the interruption in cognitive connections, the CPE should perform both in-band and out-band sensing. In-band sensing senses the channel that is being used by the BS and CPE, while the out-of-band sensing monitors the rest of the spectrum for potential candidates of usable channels. To strictly avoid harmful interference to primary users, a quiet time is allocated before each sensing (listen-before-talk), which may interrupt current data transmissions frequently. An alternative approach called Dynamic Frequency Hopping (DFH) [19] is proposed in IEEE 802.22 to cope with this drawback and provide seamless communications. By using DFH, the cognitive device keeps hopping from one channel to another. Spectrum sensing is performed in parallel with the transmission to ensure the availability of the channel that the device is hopping to.

Current Research Work

Recent research work have been conducted on issues such as primary user identification, spectrum sensing, channel state prediction, power control for interference minimization, and dynamic spectrum management/access. A spectrum-allocation and power-control scheme is proposed in [20] in order to maximize the spectrum utilization while guaranteeing the required signal to interference plus noise ratio (SINR) of each subscriber in a cognitive radio network. Spatial opportunity allocation among secondary users can be found in [21][22][23] and references therein. In [24], the problem of spectrum sharing among a single primary user and multiple secondary users is formulated and studied through a game theoretical approach.

1.2 Motivations, Key Issues and Related Works

Providing data transmissions with guaranteed QoS is of great importance in various WSN applications. QoS provisioning is the function to guarantee a certain level of performance to a data flow or to provide different priorities to different applications, users, or data flows. For example, a required data rate, jitter, delay, packet dropping probability or bit error rate may be guaranteed. A lot of the WSN applications are real-time traffic with latency requirements, and data are valid only for a limited duration and should be delivered before they expire. For example, in health care a packet indicating an abnormal event of a patient should reach the doctor as soon as possible; in environmental monitoring, a wireless smoke sensor should provide real-time recognition of smoke or fire. As a result, providing services with strict QoS requirements is becoming a key issue in future WSNs.

However, WSNs working in the license free spectrum have to share the spectrum with other networks, such as IEEE 802.11-based WLANs and IEEE 802.16-based WiMax networks. As the demands for wireless communications increase, the license free spectrum has been increasingly crowded. The coexistence of multiple networks in the same spectrum brings challenging issues [25] including spectrum utilization, security, transmission collisions and other issues between same or different wireless technologies, posing a major problem for supporting traffic with strict QoS requirements.

Using cognitive radio technology can be a promising approach to providing data transmissions in a WSN with strict QoS requirements. The low utilization of the licensed spectrum leaves a large amount of resource that can possibly be used to transmit traffic with high bandwidth and low latency requirements. Another major advantage of building a cognitive radio sensor network (CRSN) is its flexibility. There is little restriction on the air interfaces, coverage area and network topologies in a cognitive radio network. The MAC protocol and resource allocations can be designed based on the specific requirements of the services and network conditions in order to satisfy the various QoS requirements, while efficiently utilizing the radio resources.

Meanwhile, there are significant challenges to build a CRSN for providing QoS. In general, issues that exist in building other cognitive radio networks, such as spectrum sensing and spectrum allocation, common control channel, potential interference to the primary network, etc., should also be solved when building a CRSN. A good survey regarding problems and solutions for cognitive radio networks can be found in [26] and the references therein. As a secondary network, the resource availability in a CRSN depends on the activity in the primary network. The amount of radio resources available for a CRSN is random due to the random activity in the primary network. Since channel availability is not guaranteed in a CRSN, a transmission can be interrupted at any time for a random duration, QoS performance such as packet loss rate and packet transmission delay is different from that in traditional WSNs, and thus needs special attention.

There have been some efforts recently on combining WSNs and cognitive radio technology, and some general implementation issues are discussed in [27]-[28]. Possible implementations of a CRSN is presented in [29] from a system level point of view.

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Energy efficiency in a CRSN with multi-carrier modulation is studied in [30] and [31]. However, little work has been done on QoS provisioning and resource management in a CRSN.

1.3 Overview of the Thesis

In this work we consider a CRSN, where devices opportunistically access available channels in the licensed spectrum in order to serve both real-time and best effort traffic. The cluster heads (CHs) are responsible for sensing available channels for associated sensors and collecting data from them.

For the real-time traffic, we consider both bursty traffic and Poisson traffic. For the bursty traffic, a burst of packets are generated periodically from the sensors and the number of packets in each burst is random. For the Poisson traffic, packet arrivals follow a Poisson process. For each type of the traffic, an analytical model is derived and simulation results are provided for the average packet transmission delay performance, and simulation results are given for the packet loss rate performance for given maximum packet transmission delay requirements. Throughput optimization is considered for the best effort traffic. Given the number of candidate channels for each cluster, an optimization problem is formulated and solved to find the time allocated for intra- and inter-cluster communications. Given the total number of channels that can possibly be used by the CRSN, a heuristic scheme is designed to find the optimum number of candidate channels allocated to each cluster in order to maximize the total system throughput.

The remainder of the thesis is organized as follows. In Chapter 2 we first describe the basic architecture and topology of the CRSN, and capacity for a single cluster is studied at the end. Performance for different types of real-time traffic is studied in Chapter 3. In Chapter 4, throughput optimization for best effort data traffic is studied, and Chapter 5 concludes the thesis.

Chapter 2

System Description

This chapter gives an overview of the CRSN, including network topology, channel switching and channel time allocations. Capacity of a single cluster is analyzed at the end.

2.1 Overview of a CRSN

We consider a multi-cluster CRSN and adopt the cluster-tree topology defined by the ZigBee Alliance. The cluster-tree topology has better scalability than the other two topologies, namely the star and mesh topologies, defined by ZigBee Alliance, and is more suitable for large-scale sensor networks. Each CH may have multiple child CHs, but has only one parent CH. A number of sensors are associated with each CH. The CH collects data from its associated sensors, receives data from the child CHs, and then forwards data to its parent CH. All data finally reaches the sink (the root CH), where they are processed and analyzed. A level-k cluster is k hops away from the sink. Normally, the sink does not have any sensors directly associated to it. Fig. 2.1

shows an example of a CRSN with 7 clusters, where node 1 is the sink, nodes 2 and 3 are CHs at the level-1, and the other four nodes are CHs at the level-2.

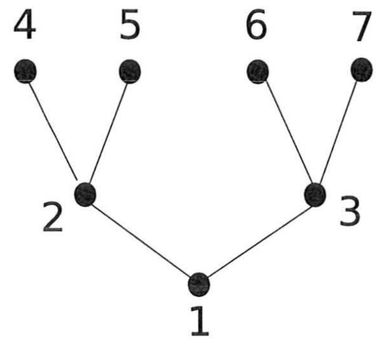


Figure 2.1: Network topology

Fig. 2.2 illustrates the timeline allocations of the sink and 2 CHs at different levels. For concise presentation, we do not distinguish between intervals for real-time and non-real-time traffic. The top one shows the timeline of the sink, which has two intervals for receiving traffic from the two level-1 CHs. Below that is the timeline of node 3, which is level-1 CH and has a period for collecting local traffic from the sensors, a period for receiving from the level-2 CHs, and another period for forwarding to the sink. The figure also shows the timeline for node 6, which is at level-2 and has a period for local traffic and a period for forwarding the received data to its parent CH at level-1.

Within a cluster, a number of sensors communicate directly with the CH. In addition to collecting data from the sensors, the CH is also responsible for sensing available channels from a number of candidate channels, allocating radio resources, and sending control signals to the sensors. In a typical CRSN, data transmissions are mainly from the sensors to the CH, and transmissions from the CH to the sensors are

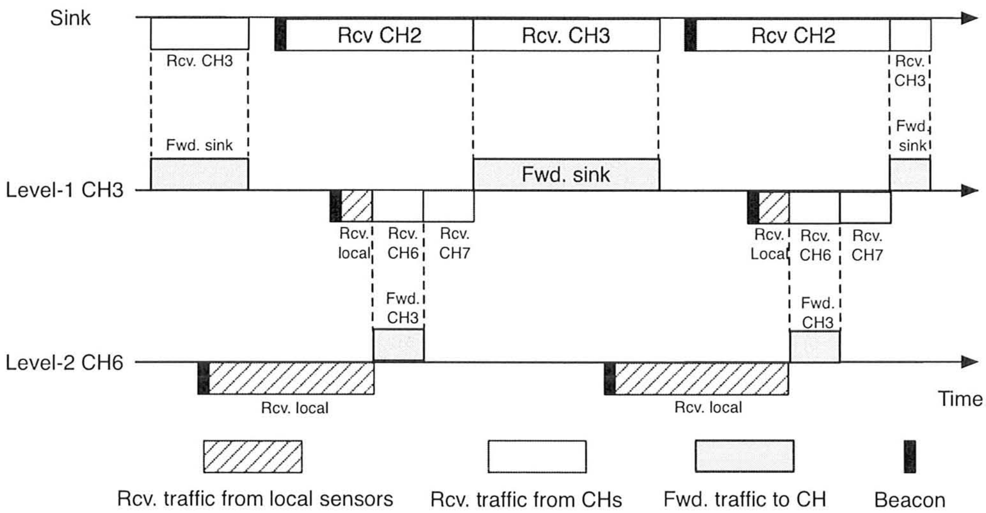


Figure 2.2: An example of the timeline allocations at different levels of a CRSN.

mainly for sending acknowledgment (ACK) frames, channel allocation messages, and other control signaling messages.

When a frequency channel is available, all transmissions between the sensors and the CH are assumed to be error-free. Co-channel interference between different clusters is not considered. Several ways can be used to avoid such interference. First, a different set of candidate channels can be assigned to neighboring clusters if there is a sufficiently large number of candidate channels. Second, if neighboring clusters have to share the same set of candidate channels, their CHs may sense the channels in different orders so that they will find different available channels with a high probability. To further avoid the clusters to work at the same channel, the CHs may exchange information about their sensed available channels through the control channel. If neighboring clusters have to share the same frequency channel, simultaneous transmissions can be avoided by carefully coordinating the timelines of the clusters using similar models as in [32][33].

2.1.1 Channel Sensing and Switching

The CRSN opportunistically accesses vacant channels in a spectrum. A dedicated control channel is used for the CH to notify the sensors about the current available channels. The CH broadcasts channel information through the control channel so that sensors can hear this message. Designing a CRSN without a dedicated control channel can be found in [34].

Each cluster requires only one available frequency channel. The CH keeps sensing the candidate channels until an available channel is found or it finds that no channel is available. The time for channel sensing can vary, especially when there is a large number of candidate channels to be sensed and each has a small probability to be available. In this case, the CH can be equipped with two radios, the first one is dedicated for channel sensing and the second one is for data communications. With the dedicated radio for channel sensing, we can assume that the CH always has the most updated information about the current available channels, and channel sensing does not cause overhead to data communications. We use T_{SW} to represent the time for the devices to switch to a new channel, if there is one available after the previous channel is lost (how to detect and notify a channel loss will be discussed later). In case the CH is only equipped with one radio, channel sensing is done before data communications, and T_{SW} should include not only the time for channel switching, but also the time for channel sensing. The value of T_{SW} should be much smaller than the amount of time for data communications so that the system can have reasonable capacity and support the real-time traffic with small delay. In such a case, the number of candidate channels should be small and each channel should have a relatively high probability of being available, since having a large number of candidate channels can introduce long sensing delay and negatively affect the network performance as demonstrated in [35]. Therefore, in either the two-radio or one-radio case, we can assume a fixed value for T_{SW}.

2.1.2 Detecting and Notifying a Channel Loss

The CRSN must vacate a channel when a primary user is present. Once an available channel becomes unavailable, the status change can be realized by the CH immediately, but it may take time for a sensor to realize the channel loss. To help the sensors keep track of the channel availability, the CH sends back an ACK to the sensors for every correctly received packet. If a sensor does not receive an ACK in time after transmitting a data packet, it considers that the current channel becomes unavailable and stops transmitting immediately. Obviously, there can be other reasons, such as channel fading, that cause transmission failures in the CRSN. Stopping transmissions in this case is a conservative way to reduce unnecessary interference to the primary network.

Strict synchronization between the sensors and their associated CH is required. Beacons are broadcast periodically by the CH in the current working channel and used for synchronization between the CH and the sensors. When the current working channel becomes unavailable, the CH stops broadcasting the beacons, and its associated sensors realize the channel loss in the next scheduled beacon time and stop their transmissions. Having more beacons can help the sensors know the availability of the current channel in time and reduce unnecessary transmissions.

2.2 MAC Layer

We adopt the IEEE 802.15.4 MAC protocol as it is one of the most popular standards for WSNs. The channel time is divided into equal length superframes (SFs) and we use T_{SF} to denote the duration of an SF. The SF time is divided into intervals for intra-cluster and inter-cluster communications. The intra-cluster time is for the CH to collect data from the sensors, and the inter-cluster time is to forward data between CHs. Due to the opportunistic channel access, the amount of available channel time in each SF is a random variable. All real-time traffic is transmitted using the guaranteed time slots (GTSs) with contention free transmissions in order to achieve small transmission delay. Communications between the CHs also use the GTS periods in order to achieve reliable transmissions and efficient channel utilization. Non-real-time BE data within a cluster are collected in the contention access period (CAP). The timeline allocation of a CH is illustrated in Fig. 2.3, where the activities above the timeline are for transmitting data traffic from the CH to its parent CH, and the activities below the timeline are for receiving data traffic from local sensors or child CHs. At the beginning of each SF, there is a small period, T_b, for broadcasting the beacon and other control information such as channel time allocations.

2.3 Capacity

2.3.1 Capacity Analysis

Below we analyze the capacity of a single-cluster CRSN in terms of the maximum number of sensors that can be supported, given the average traffic load of each sensor. Since delay performance is not explicitly considered in the analysis, the capacity below

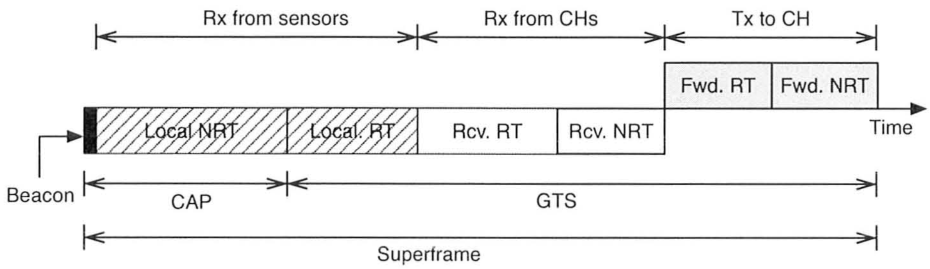


Figure 2.3: Superframe structure

is the upper bound when considering real-time traffic.

As the primary user activities are random, the availability of a channel is random to a CH. A channel available interval (CAI) is a continuous interval during which there is no primary user activity in a channel, and a channel unavailable interval (CUI) is an interval during which the primary user keeps occupying the channel.

We consider that all channels have the same statistical activities. That is, they all have the same distribution for their CAIs and the same distribution for their CUIs. Furthermore, the availabilities of the channels are independent of each other. Let random variables T_{on} and T_{off}, respectively, represent the duration of a CAI and CUI. We assume that both T_{on} and T_{off} are exponentially distributed with mean $\overline{T}_{on}$ and $\overline{T}_{off}$, respectively, and $P_{on} = \frac{\overline{T}_{on}}{\overline{T}_{on}+\overline{T}_{off}}$ is the probability that a channel is available. Given that there are C channels in total, the probability of outage is $P_{out} = (1 - P_{on})^C$ when all the C channels are unavailable. The duration of a channel outage interval (COI) is represented by random variable T_{out}, which is exponentially distributed with mean $\overline{T}_{out} = \frac{\overline{T}_{off}}{C}$.

The channel time of a CH may consist of one or multiple CAIs and COIs. There can be one or zero COIs between two successive CAIs. Let R represent the period from the end of one CAI to the end of the next CAI. We find that R is a renewal process that can have two types of renewal intervals (RIs). The first type contains only a CAI as R_2 and R_4 shown in Fig. 2.4, and the second type contains a CAI followed by a COI as R_1 and R_3 in the figure.

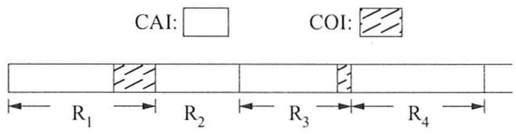


Figure 2.4: Renewal process

The average duration of the first type RI is $\overline{T}_{on}$, and that of the second type is $\overline{T}_{on} + \overline{T}_{out}$. The average channel available time in each RI is $\overline{T}_{on}$, and the average unavailable channel time in each RI is $\frac{\overline{T}_{off}}{C}P_{out}$. Overall, the average duration of the renewal interval is given by:

$$\overline{R} = (1 - P_{out})\overline{T}_{on} + P_{out}(\overline{T}_{on} + \frac{\overline{T}_{off}}{C}) = \overline{T}_{on} + \frac{\overline{T}_{off}}{C}P_{out}. \tag{2.1}$$

Consider a time interval of duration T_L^{res} reserved for local traffic. Since there is one channel switching between any two successive RIs, the average number of RIs in the reserved time interval is equal to the average number of channel switchings and is given by $S = \frac{T_L^{res}}{\overline{R}}$. Therefore, the mean amount of time that can be used for serving the local real-time traffic in the considered cluster is

$$T_{L,k} = T_L^{res} - \frac{\overline{T}_{off}}{C}P_{out}S - T_{SW}S = \frac{\overline{T}_{on}}{\overline{R}}T_L^{res} - T_{SW}S. \tag{2.2}$$

Let $\overline{M}_0$ be the average number of packets generated by each sensor during an SF, then the maximum number of sensors that can be supported is given by

$$N_{\max} = \left\lfloor \frac{T_{L,k}}{T_d\,\overline{M}_0} \right\rfloor . \tag{2.3}$$

2.3.2 Numerical Results

Table 2.1: Default Simulation Parameters

Parameter	Value
Total number of channels C	5
Average duration of a CAI $\overline{T}_{on}$	100ms
Average duration of a CUI $\overline{T}_{off}$	100ms
Duration of superframe T_{SF}	52ms
Time for channel switching T_{SW}	1ms
Packet transmission time T_d	5ms
Duration of reserved time interval T_L^{res}	50ms

Figs. 2.5 and 2.6 show the cluster capacity, assuming that each sensor generates 1 data packet in every 5 SFs, and each packet transmission takes $T_d = 5$ms. The simulation and analysis curves are well matched, showing the accuracy of the mathematical model. The slight differences between simulation and analysis curves are due to that channel switching time T_{SW} is neglected in the analysis. The capacity increases with P_{on} and C in general. However, when P_{on} (or C) is sufficiently large, having a larger P_{on} (or C) has little effect on the capacity because the capacity is limited by the reserved time interval.

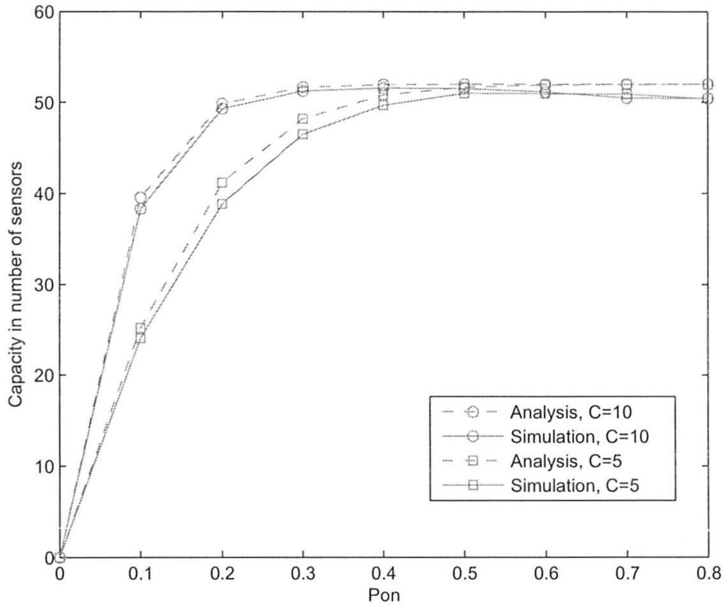


Figure 2.5: Capacity vs. P_{on}

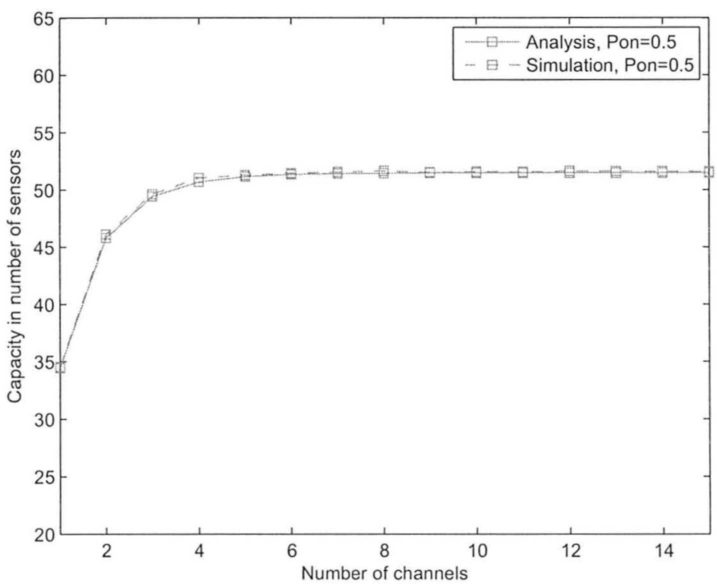


Figure 2.6: Capacity vs. number of channels

Chapter 3

Performance of Real-time Traffic

In this chapter we focus on real-time traffic between the sensors and the CH within a cluster. This is either because the sink is co-located with the CH, or the CH can forward the collected real-time data to a remote data sink through high speed links. In either case, data transmission delay between the CH and the sink is much smaller, compared to that between the sensors and the CH, and can be neglected.

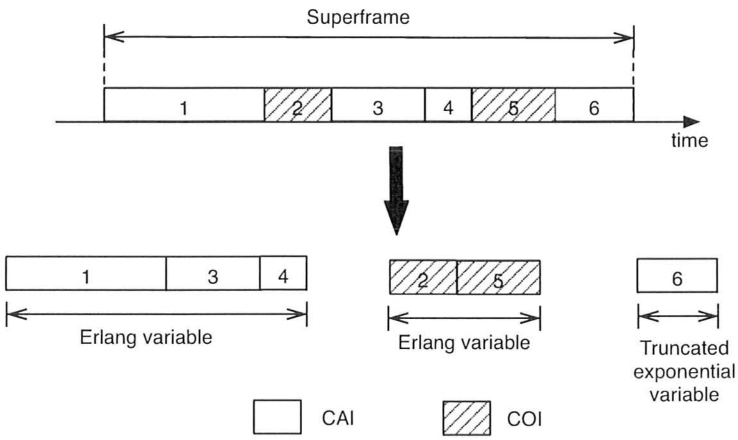
In the remainder of this chapter, we first find the distribution of available channel time in the CRSN. Based on this, analytical models are developed to find average packet transmission delay for bursty traffic and Poisson traffic. The analysis is verified by comprehensive computer simulations. In addition, simulation results regarding the packet loss rate are also shown, given the maximum delay requirements of the traffic.

3.1 Distribution of Available Channel Time

In each SF, the CH reserves an amount of T_L^{res} of the radio time for collecting real-time traffic from its associated sensors. As introduced in Section 2.3.1, the radio time of a CH may consist of one or multiple CAIs and COIs. So the reserved interval may also consist of one or multiple CAIs and COIs. If the reserved interval ends in the middle of a CAI or COI, the amount of the CAI or COI time that belongs to the reserved interval is referred to as a "truncated CAI (TCAI)" or "truncated COI (TCOI)". Since the distribution of the TCAI (and TCOI) is different from that of the CAI (and COI) that ends "naturally" when the channel status changes, we refer to the latter as non-truncated CAI (and non-truncated COI), or NCAI (and NCOI) in brief. The duration of each NCAI or NCOI follows an exponential distribution, while that of a TCAI or TCOI does not. We use U ($U \geq 0$) and V ($V \geq 0$), respectively, to denote the number of NCAIs and NCOIs in the reserved time interval, and U' and V', respectively, to denote the number of TCAIs and TCOIs. We then have $U', V' \in \{0, 1\}$ and $U' + V' = 1$. The case of $U' = V' = 0$ is not considered since the probability that the reserved time interval ends at exactly the same time as a NCAI or NCOI ends is zero. For U and V, we have $V \leq U + 1$. The equality holds when the reserved time interval starts with a NCOI and ends with a TCAI, and there is a NCOI between any two successive NCAIs. It is possible, however, that there is no NCOI between two successive NCAIs, and this happens when a new channel is available immediately after the previous channel is lost. In this case, $V < U + 1$. For given $U = u$, the probability of $V = v$ can be found using Bernoulli Polynomials as

$$B(u+1, v, P_{out}) = \binom{u+1}{v} P_{out}^{v} (1 - P_{out})^{u+1-v}. \tag{3.1}$$

The total available channel time in the reserved time interval is a sum of U NCAIs and a TCAI if $U' = 1$. The duration of each NCAI follows an exponential distribution with mean $\overline{T}_{on}$. As a result, the summation of them, which is the total amount of



the NCAI time in the reserved time interval, follows an Erlang distribution. Fig. 3.1 shows the summations of all NCAIs and all NCOIs respectively.

When $U = u \geq 1$, the total amount of the NCAI time in the reserved time interval follows an Erlang-u distribution with a pdf given by

$$p_{e,on}(t, u) = \frac{t^{u-1} e^{-\frac{t}{\overline{T}_{on}}}}{\overline{T}_{on}^{u}(u-1)!}. \tag{3.2}$$

Similarly, the amount of total unavailable channel time in the reserved time interval is a sum of V ($V \geq 0$) NCOIs and a TCOI if $V' = 1$. When $V = v \geq 1$, the total amount of the NCOI time in the reserved time interval follows an Erlang-v distribution with a pdf given by

$$p_{e,out}(t, v) = \frac{C^{v} t^{v-1} e^{-\frac{Ct}{\overline{T}_{off}}}}{\overline{T}_{off}^{v}(v-1)!}. \tag{3.3}$$

Notations $p_{e,on}(t, u)$ and $p_{e,out}(t, v)$ defined in (3.2) and (3.3), respectively, will be used later on in order to make concise expressions when deriving the pdf of T_a.

The distribution of T_a is dependent on U, V, U' and V'. Since U' and V' cannot all be 1 for the same reserved time interval, we consider two cases, case (1) when $U' = 1$ and $V' = 0$, and case (2) when $U' = 0$ and $V' = 1$. For each of these two cases, we further consider different subcases as shown in Fig. 3.1 based on values of U and V. Below we treat each (sub)case separately.

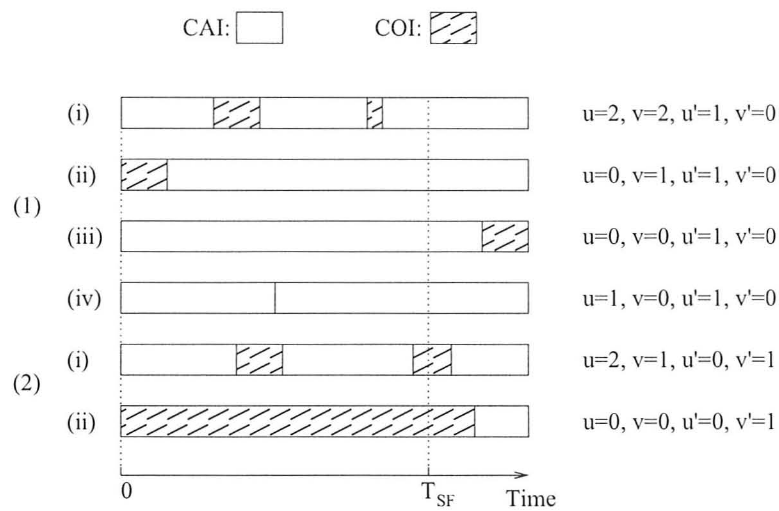


Figure 3.1: Timelines of CAIs and COIs vs. a SF

Case (1): $U' = 1$ and $V' = 0$.

In this case, there is no TCOI in the reserved time interval, and $T_L^{res} - T_a$ gives the total amount of NCOI time, which is also the total amount of the unavailable channel time in the reserved time interval. There are four sub-cases depending on whether the reserved time interval includes at least one NCAI ($U > 0$) or at least one NCOI ($V > 0$).

Subcase (i), $U > 0$ and $V > 0$. There is at least one NCAI and one NCOI in the reserved time interval. If the total amount of the NCAI time is t, then $0 \leq t < T_a$ and $T_a - t$ gives the amount of TCAI time. As the duration of the reserved time interval is fixed at T_L^{res}, the variables T_a, U, and V are dependent on each other and their joint pdf is given by

$$f_1(t_a, u, v) = \int_0^{t_a-} p_{e,on}(t, u)\ p_{e,out}(T_L^{res} - t_a, v)\ B(u+1, v, P_{out})\ \text{Pr.}\{T_{on} > t_a - t\}dt, \tag{3.4}$$

where $p_{e,on}(t, u)$ and $p_{e,out}(T_L^{res} - t_a, v)$, respectively, give the pdf of having u NCAIs with total duration of t and v NCOIs with total duration of $T_L^{res} - t_a$, Pr.$\{T_{on} > t_a - t\}$ gives the probability that there exists a TCAI in the reserved time interval, and the upper limit of the integral (t_a-) is due to that t should be smaller than t_a so that there is a non-zero TCAI.

Subcase (ii), $U = 0$ and $V > 0$. In this case, V can only be 1, and the reserved time interval includes a NCOI followed by a TCAI. The joint pdf is given by

$$f_1(t_a, 0, v) = P_{out}\ p_{e,out}(T_L^{res} - t_a, 1)\ \text{Pr.}\{T_{on} \geq t_a\}, \tag{3.5}$$

where P_{out} gives the probability of channel outage at the beginning of the reserved time interval, $p_{e,out}(T_L^{res} - t_a, 1)$ gives the pdf of the NCOI with duration $T_L^{res} - t_a$, and Pr.$\{T_{on} \geq t_a\}$ gives the probability that there exists a TCAI lasting for t_a time.

Subcase (iii), $U = V = 0$. There is no NCOI or NCAI in the reserved time interval, and the entire reserved time interval is a TCAI. Therefore, $T_a = T_L^{res}$. This happens when there is at least one channel available at the beginning of the SF and the channel is available for the entire reserved time interval. Then we have

$$\text{Pr.}\{T_a = T_L^{res}, U = V = 0\} = (1 - P_{out})\text{Pr.}\{T_{on} \geq T_L^{res}\}. \tag{3.6}$$

Subcase (iv), $U > 0$ and $V = 0$. Since both $V = 0$ and $V' = 0$, there is no channel outage, and $T_a = T_L^{res}$. Meanwhile, as $U > 0$, there is at least one channel switching in the reserved time interval. We then have

$$\Pr.\{T_a = T_L^{res}, U > 0, V = 0\} = \sum_{u=1}^{\infty} (1 - P_{out})^{u+1} \int_0^{T_L^{res}-} p_{e,on}(t,u) \Pr.\{T_{on} > T_L^{res} - t\} dt \tag{3.7}$$

where $(1 - P_{out})^{u+1}$ is the probability that the reserved time interval is not in outage at the beginning and after every NCAI, $p_{e,on}(t, u)$ gives the pdf of the NCAI time, and $\Pr.\{T_{on} > T_L^{res} - t\}$ gives the probability of existing one TCAI.

Subcases (iii) and (iv) in Case (1) include all the possible scenarios to have $T_a = T_L^{res}$. Combining (3.6) and (3.7) we can find $\Pr.\{T_a = T_L^{res}\}$ as

$$\begin{aligned}\Pr.\{T_a = T_L^{res}\} &= (1 - P_{out})\Pr.\{T_{on} \geq T_L^{res}\} \\ &\quad + \sum_{u=1}^{\infty} (1 - P_{out})^{u+1} \int_0^{T_L^{res}-} p_{e,on}(t,u) \Pr.\{T_{on} > T_L^{res} - t\} dt.\end{aligned} \tag{3.8}$$

By combining all the four subcases we can find the overall pdf of t_a in case (1) as

$$f_1(t_a) = \sum_{u=0}^{\infty} \sum_{v=1}^{u+1} f_1(t_a, u, v) + \delta(t_a - T_L^{res})\Pr.\{T_a = T_L^{res}\}. \tag{3.9}$$

Case (2): $U' = 0$ and $V' = 1$.

In this case, $0 \leq V \leq U$. If the total amount of NCOIs is t, then $0 \leq t < T_L^{res} - T_a$, and $T_L^{res} - T_a - t$ gives the duration of the TCOI.

Subcase (i), $U > 0$. The joint pdf of T_a, U and V is given by

$$f_2(t_a, u, v) = p_{e,on}(t_a, u) B(u, v, P_{out}) \int_{t=0}^{(T_L^{res} - t_a)-} p_{e,out}(t, v) \Pr.\{T_{out} > T_L^{res} - t_a - t\} dt \tag{3.10}$$

for $0 < v \leq u$, where $p_{e,on}(t_a, u)$ and $p_{e,out}(t, v)$, respectively, give the pdf of the total NCAI and total NCOI time, and $\Pr.\{T_{out} > T_L^{res} - t_a - t\}$ is the probability of existing one TCOI.

When $V = 0$, the unavailable channel time is the TCOI. We have

$$f_2(t_a, u, 0) = p_{e,on}(t_a, u)\ (1 - P_{out})^u \int_{t=0}^{(T_L^{res} - t_a)-} \Pr.\{T_{out} \geq T_L^{res} - t_a - t\} dt. \tag{3.11}$$

Subcase (ii), $U = 0$. The entire reserved time interval is in outage and $T_a = 0$. The probability of this is given by

$$\Pr.\{T_a = 0\} = \Pr.\{T_{out} \geq T_L^{res}\} = e^{-\frac{C T_L^{res}}{T_{off}}}. \tag{3.12}$$

Combining both the subcases, the overall pdf of T_a in case (2) is given by

$$f_2(t_a) = \sum_{u=1}^{\infty} \sum_{v=0}^{u} f_2(t_a, u, v) + \delta(t_a)\ \Pr.\{T_a = 0\}. \tag{3.13}$$

Further combining (3.9) and (3.13) we find the pdf of T_a as

$$f(t_a) = f_1(t_a) + f_2(t_a). \tag{3.14}$$

3.2 Performance for Bursty Traffic

3.2.1 Analytical Model for Average Packet Transmission Delay

We consider that M packets are generated from the sensors at the same time right after the beginning of each SF [1], where M is a random variable. In a practical system, each sensor may have a certain probability to send data packets to the CH at the beginning of each SF, and M represents the total number of packets sent by all the sensors in an SF. We assume that the packets are stored in a virtual buffer until they are transmitted, and use Z to count the total number of packets in the buffer. The distribution of Z can be complicated as the packet arrival process is random, the server availability (or service rate) is random and does not follow a standard distribution, and therefore the service system does not fit any standard queueing model. Instead of finding the distribution of Z directly, we define a random variable X as the number of buffered packets at the end of each SF. That is, X is the sample of Z at discrete time instants. We then find that X is a Markov chain embedded in Z, since the buffer occupancy at the end of the current SF only depends on its value at the end of the previous SF and the packet arrivals and channel availability in the current SF, but not at earlier time. Below we first find the state transition probability of X. Based on this, the steady-state probability of X can be found. The mean of Z can then be found.

Define T_d as the packet transmission time, which is the amount of time for transmitting one data packet, including the time for transmitting the ACK but not any

[1] Other cases when packets are generated at different and deterministic time instants can be derived similarly but the bursty arrival case results in more concise formulas.

time caused by channel unavailable and channel switching. Channel time is divided into equal length time slots each with duration of T_d. Assuming that both T_{SF} and T_L^{res} are integer multiples of T_d, $K_{\max} = \frac{T_{SF}}{T_d}$ gives the total number of time slots in an SF, and $K = \frac{T_L^{res}}{T_d}$ is the number of time slots in the reserved interval for the real-time traffic. We further define $p_t(k)$ as the probability of T_a duration that is equivalent to the amount of time for serving k and only k packets in the reserved time interval. Given the distribution of T_a, we can find $p_t(k)$ as

$$p_t(k) = \begin{cases} \Pr.\{T_a < T_d\}, & \text{if } k = 0, \\ \Pr.\{kT_d \le T_a < (k+1)T_d\}, & \text{if } 1 \le k < K, \\ \Pr.\{T_a = KT_d\}, & k = K, \\ 0, & k < 0 \text{ or } k > K. \end{cases} \tag{3.15}$$

Consider a typical SF as the reference SF. Given $M = m$ and the buffer occupancy at the end of the previous SF as $X = x$, there are $x + m$ packets in the virtual buffer at the beginning of the reference SF, assuming the buffer size is sufficiently large, and the probability that $X = x^{'}$ at the end of the reference SF is given by

$$Q_{xx',m} = \begin{cases} \sum_{k=x+m}^{K} p_t(k), & \text{if } x^{'} = 0 \text{ and } x + m \le K, \\ p_{x+m-x'}, & \text{if } x + m - K \le x^{'} \le x + m, \\ 0, & \text{otherwise}. \end{cases} \tag{3.16}$$

The unconditional transition probability of X then can be found as

$$Q_{xx'} = \sum_{m=0}^{\infty} Q_{xx',m} \Pr.\{M = m\}. \tag{3.17}$$

The steady-state probability of X, $\Pr.\{X = x\}$, can then be found from (3.17). Let $Y = y$ be the number of packets served in the reference SF. The distribution of Y for given X and M is related to the transition probability of X and given by

$$\Pr.\{Y = y|X = x, M = m\} = \begin{cases} Q_{x,\ x+m-y,\ m}, & 0 \leq y \leq \min\{K, x+m\}, \\ 0, & \text{otherwise.} \end{cases} \tag{3.18}$$

Accurate analysis is difficult as the available channel time is divided into discontinuous and random intervals. However, we can use an approach to find the upper and lower delay bounds. First, if we can move all the CAIs (both NCAIs and TCAIs) in front of the COIs in the reserved time interval, the lower bound of the buffer occupancy can be found. In this case, the buffer occupancy Z is $x+m$ at the beginning of the SF. It keeps decreasing by one in every time slot until it becomes $x+m-y$, and then becomes constant for the rest of the SF. This lower bound of the conditional buffer occupancy can be found as

$$\mathrm{E}[Z|m, x, y] = \frac{\sum_{j=0}^{y-1}(x+m-j) + (x+m-y)(K_{\max}-y)}{K_{\max}}, \tag{3.19}$$

where the first term in the numerator on the right-hand side of (3.19) is for the period when the buffer occupancy keeps decreasing, and the second term is for the period when the buffer occupancy is constant.

On the other hand, if we can move all the COIs in front of all the CAIs during the reserved time interval, the upper bound of the buffer occupancy can be found. In this case, the buffer occupancy keeps constant at $x+m$ for $K-y$ time slots, then decreases by one in every time slot until it becomes $x+m-y$ at the end of the reserved time interval, and then keeps constant for the rest of the SF. In this way, we can find the upper bound of the buffer occupancy whose conditional mean is given by

$$\mathrm{E}[Z|m,x,y] = \frac{(x+m)(K-y) + \sum_{j=0}^{y-1}(x+m-j) + (x+m-y)(K_{\max}-K)}{K_{\max}} \quad (3.20)$$

The mean buffer occupancy can be found as

$$\mathrm{E}[Z] = \sum_{m=1}^{\infty}\sum_{x,y=0}^{\infty} \mathrm{E}[Z|m,x,y]\mathrm{Pr.}\{X=x\}\mathrm{Pr.}\{Y=y|X=x,M=m\}\mathrm{Pr.}\{M=m\}. \quad (3.21)$$

Let $\overline{M}$ denote the mean of M. Using the Little's Formula, the mean delay can be found as

$$\mathrm{E}[D] = \frac{\mathrm{E}[Z]}{\overline{M}/T_{SF}}. \quad (3.22)$$

Using (3.19), (3.21) and (3.22), we can find the low bound of the average packet transmission delay, and using (3.20), (3.21) and (3.22) we can find the upper bound of the average packet transmission delay.

3.2.2 Numerical Results

We consider a generic cluster with one CH and N_s sensors. The system setting is the same as described in Chapter 2. There are C homogeneous channels all with the same statistics of being available and unavailable to the CRSN. The durations of the NCAIs and NCOIs are exponentially distributed. Each sensor node generates one packet at the beginning of each SF with probability P_b. Default simulation parameters can be found in Table 3.1.

Table 3.1: Default Simulation Parameters

Parameter	Value
Total number of channels C	5
Average duration of a NCAI T_{on}	100ms
Average duration of a NCUI T_{off}	100ms
Duration of superframe T_{SF}	52ms
Time for channel switching T_{SW}	2ms
Number of sensors N_s	30
Packet transmission time T_d	5ms
Duration of reserved time interval T_L^{res}	50ms
Packet generating probability for bursty traffic P_b	0.2
Packet dropping threshold:	$6T_{SF}$(312ms)

We can see in Figs. 3.2 and 3.3 that when the number of sensors is small, the simulated delay values are very close to the derived lower bounds. In this case, queueing delay due to bursty arrivals is small, and most packets, after being generated at the beginning of an SF, can be transmitted during the early portion of the same SF as soon as the channel is available. On the other hand, when the number of sensors is larger, the simulated delay becomes closer to the upper bound. This is because the queuing delay caused by the bursty arrivals starts dominating the packet transmission delay and more packets have to be buffered and served in later portion of the SF. As the number of sensors is further increased, the lower bound and upper bound are getting closer to each other. This is because the delay caused by both the bursty packet arrivals and the channel outage increases.

Given the number of sensors, we can also see in Figs. 3.4 and 3.5 that the simulation results are closer to the upper bound when the number of channels is smaller, and the simulation results are closer to the lower bound when the number of channels is larger. This is due to the similar reason as above. When there are more channels, there is more available channel time in each SF, then fewer packets are buffered. In this case, more packets can be served during the early portion of the same SF after they are generated. Therefore, the simulation results are closer to the lower bound. When the number of channels is sufficiently large, further increasing it does not improve the delay performance very much since the delay caused by bursty arrivals of the packets dominates the overall transmission delay.

Figs. 3.6 and 3.7 show that the packet transmission delay decreases with P_{on}. When the number of candidate channels is small, having a larger P_{on} can significantly reduce the average delay. On the other hand, when P_{on} is sufficiently large, further increasing it does not help reduce the delay because the delay is now dominated by the packet transmission time and queueing delay due to bursty arrivals but not channel availability.

Given the maximum transmission delay as $6T_{SF}$, packets with delay exceeding this limit are dropped. The packet drop rate is defined as the ratio of dropped packets to the total number of packets. It is seen from Figs. 3.8 and 3.9 that very low drop rate can be achieved when the system is stable. For example, when $N_s = 35$ and $P_{on} = 0.22$, the packet drop rate is below 0.01, and when $N_s = 45$ and $P_{on} = 0.36$, the packet drop rate is below 0.01.

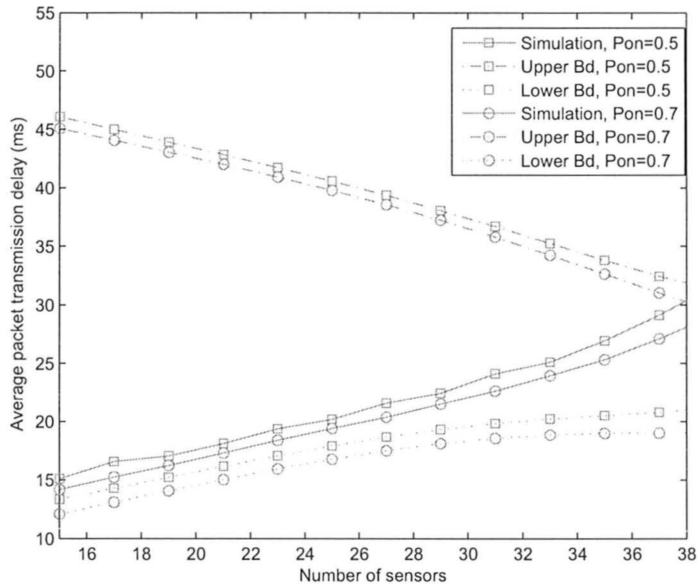


Figure 3.2: Bursty traffic: delay vs. number of sensors, with different P_{on}.

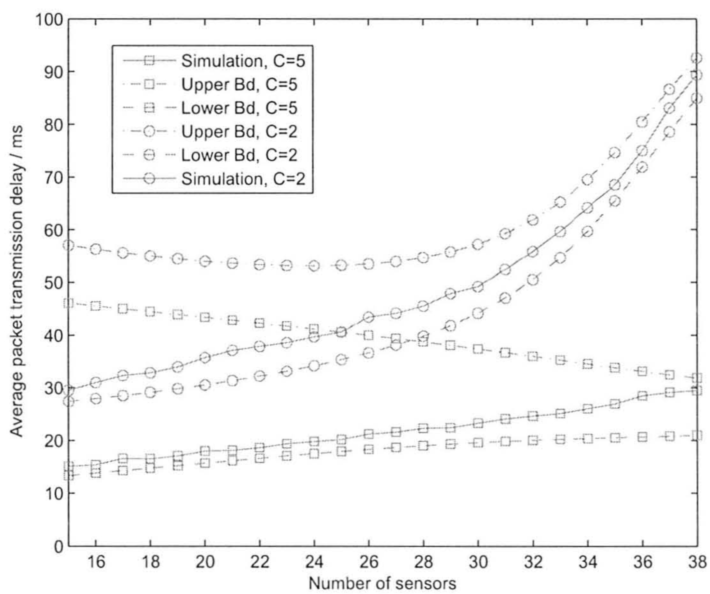


Figure 3.3: Bursty traffic: delay vs. number of sensors, with different C.

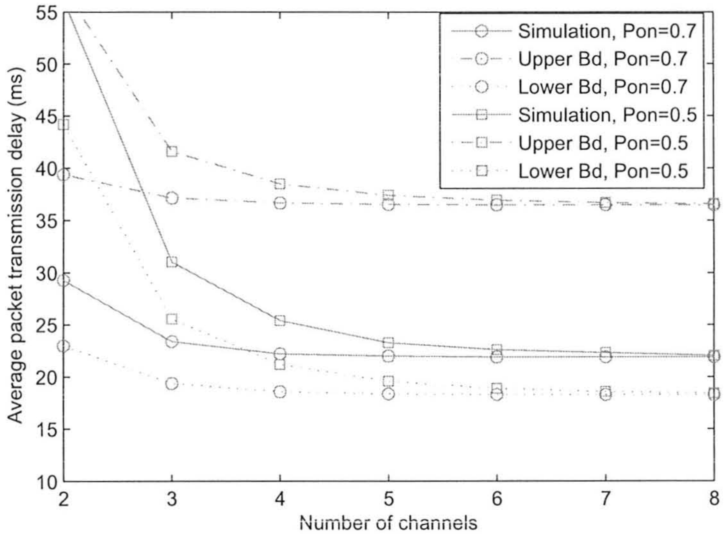


Figure 3.4: Bursty traffic: delay vs. number of channels, with different P_{on}.

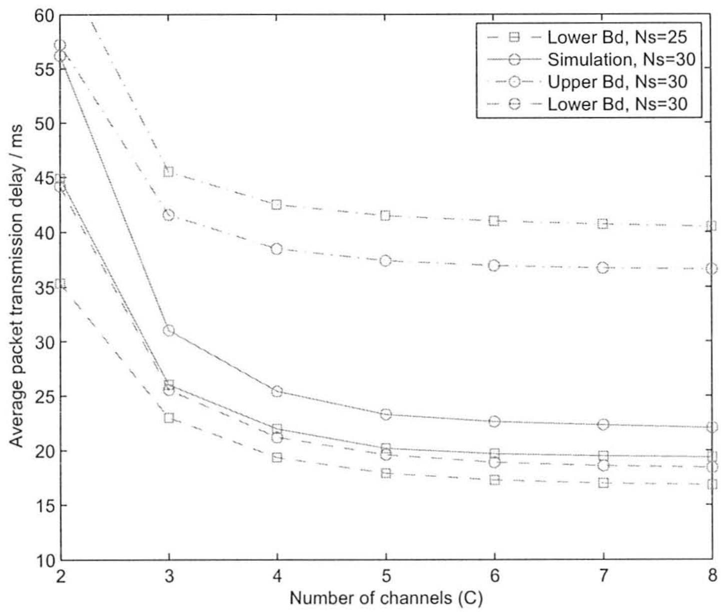


Figure 3.5: Bursty traffic: delay vs. number of channels, with different N_s.

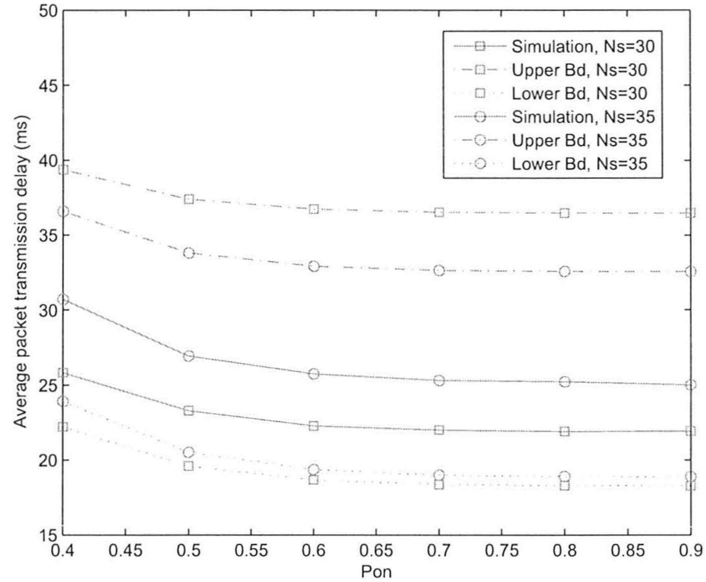


Figure 3.6: Bursty traffic: delay vs. P_{on}, with different N_s.

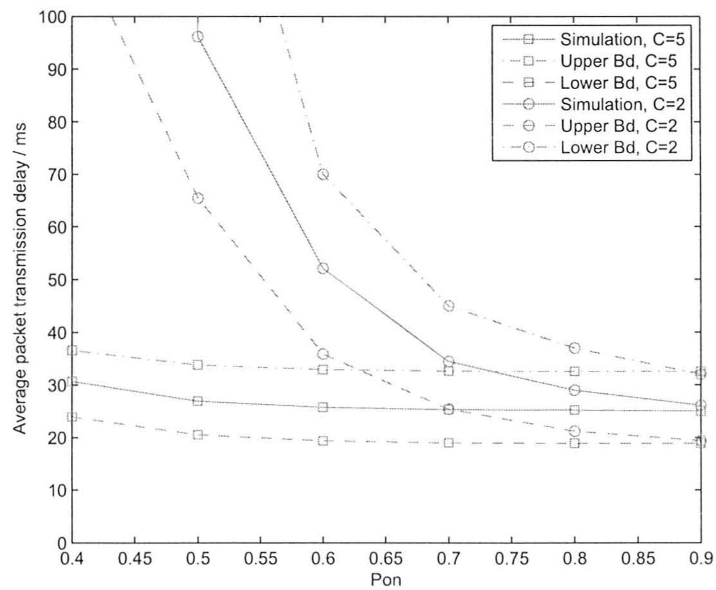


Figure 3.7: Bursty traffic: delay vs. P_{on}, with different C.

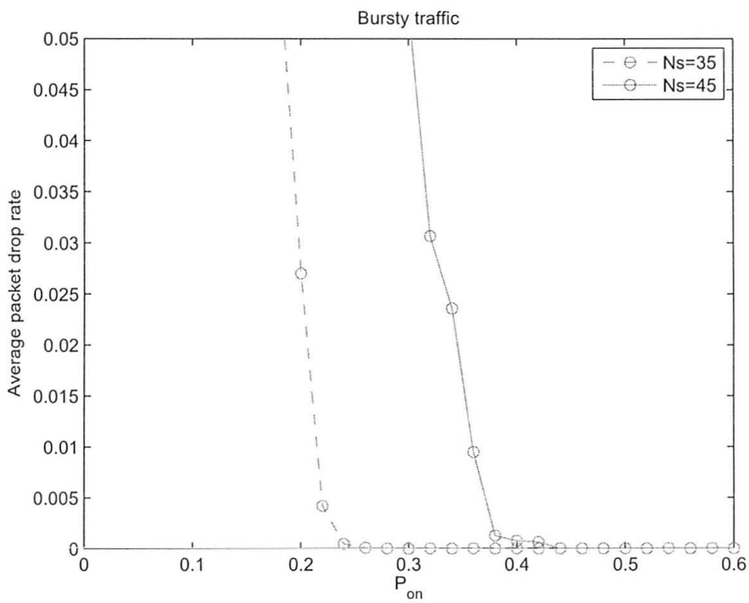


Figure 3.8: Bursty traffic: packet drop rate vs. P_{on}, with different N_s.

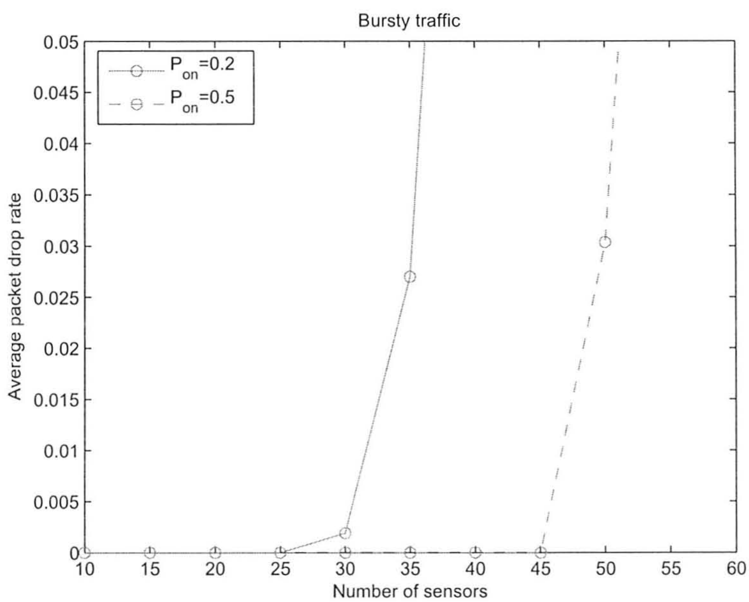


Figure 3.9: Bursty traffic: packet drop rate vs. number of sensors, with different P_{on}.

3.3 Performance for Poisson Traffic

3.3.1 Analytical Model for Average Packet Transmission Delay

In the considered CRSN, the delay for a packet transmission can be caused by i) the available channel is busy in serving other packets that arrive earlier, ii) no channel is available during the reserved time interval, and iii) the CH radio time is not reserved for the real-time traffic. We consider the unavailable channel time during the reserved time interval as part of the *Packet Service Time* (PST), and the unreserved time as the server vacation time. Accurate analysis can be complicated due to that the COIs can occur randomly at any time during the reserved time interval and their durations are also random. An approximation to the PST can be found by assuming that the available (and unavailable) channel time is evenly distributed in the reserved time interval. That is, if the total amount of the available channel time is T_a in the reserved time interval of duration T_L^{res}, then in every time unit the amount of available channel time is T_a/T_L^{res}. In order to serve one packet, the amount of available channel time in each PST of duration τ is T_d. That is, $\tau = \frac{T_d T_L^{res}}{T_a}$ for $T_a > 0$. With this approximation, all the PSTs in the same SF are of the same length. However, since T_a is random, τ is also random when considering different SFs. The case of $T_a = 0$ is ignored in the derivation, since the probability of channel outage for the entire reserved interval should be very low in a practical network. Then we can find

E[τ] and E[τ^2] approximately as

$$\mathrm{E}[\tau] = \int_{0+}^{T_L^{res}} \frac{T_d T_L^{res}}{t_a} f(t_a) dt_a, \quad (3.23)$$

$$\mathrm{E}[\tau^2] = \int_{0+}^{T_L^{res}} \left(\frac{T_d T_{SF}}{t_a}\right)^2 f(t_a) dt_a. \quad (3.24)$$

The unreserved channel time of duration $T_{SF} - T_L^{res}$ is treated as the server vacation time. The service system can then be modeled as an M/G/1 queue with vacation and the average packet transmission delay can be found approximately as

$$\mathrm{E}[D] = \mathrm{E}[\tau] + \frac{\lambda \mathrm{E}[\tau^2]}{2(1 - \lambda/\mathrm{E}[\tau])} + \frac{T_{SF} - T_L^{res}}{2}. \quad (3.25)$$

3.3.2 Numerical Results

Table 3.2: Default Simulation Parameters

Parameter	Value
Total number of channels C	5
Average duration of a NCAI T_{on}	100ms
Average duration of a NCUI T_{off}	100ms
Duration of superframe T_{SF}	52ms
Time for channel switching T_{SW}	2ms
Number of sensors N_s	30
Packet transmission time T_d	5ms
Duration of reserved time interval T_L^{res}	50ms
Packet inter-arrival time for Poisson traffic T_p	260ms

We consider the same generic cluster with one CH and N_s sensors as used in Section 3.2.2. The packet arrivals follow a Poisson process, and the inter-arrival time between two consecutive packets generated by a given sensor is T_p. Default parameters are listed in Table 3.2, where the values of T_p is selected so that the average packet generating rate of each sensor is the same as that for the bursty case in Section 3.2.2.

Figs. 3.10 and 3.11 show that, the delay decreases with P_{on}. The difference between the simulation and analytical results is relatively large when P_{on} is small. This is because in this case the outage probability is high, or the probability of $T_a = 0$ is high, while this is not considered in the analysis. As P_{on} increases, the difference between the simulation and analytical results becomes small.

In Figs. 3.12 and 3.13 we can see that having a larger number of channels results in relatively shorter delay. There is a relatively large difference between the simulation and analysis when the number of channels is small. This is due to the same reason as described above. That is, the outage probability is high, or the probability of $T_a = 0$ is high, which is not considered in the analysis. As C increases, the outage probability decreases exponentially. When C is relatively large, for example, larger than 4 when $P_{on} = 0.7$ and larger than 5 when $P_{on} = 0.5$, the simulation results match the analysis very well.

Figs. 3.14 and 3.15 show the packet drop rate for the Poisson traffic. In Fig. 3.14, we can see that when number of sensors is 35, the average packet drop rate is less than 1% for $P_{on} > 0.2$. When the number of sensors is increased to 45, the drop rate falls below 1% for $P_{on} > 0.36$. Similar results can be found in Fig. 3.15.

By comparing the results in Figs. 3.6 and 3.10, we can see that the bursty traffic in general experiences longer average delay than the Poisson traffic. For the bursty traffic, packets arrive at the same time (beginning of an SF), any packet in queue has to wait till all packets ahead of it are processed. As a result, for most of the packets (except the first one) queuing delay is inevitable.

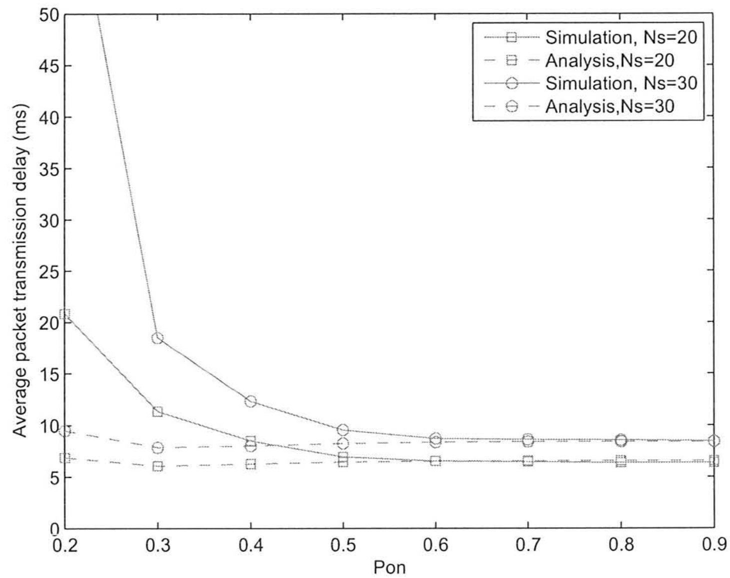


Figure 3.10: Poisson traffic: delay vs. P_{on}, with different N_s.

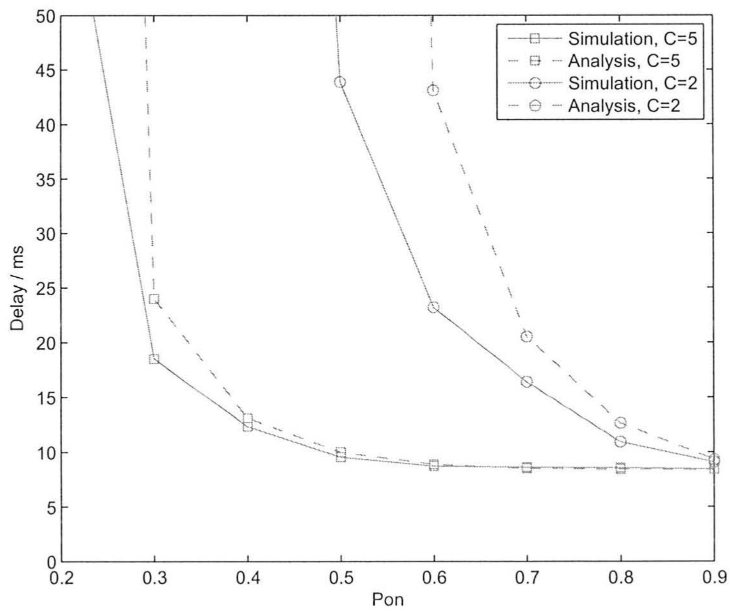


Figure 3.11: Poisson traffic: delay vs. P_{on}, with different C.

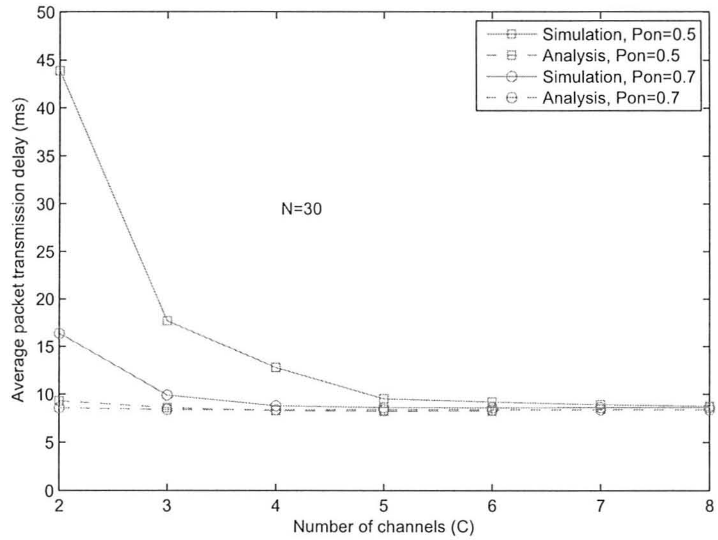


Figure 3.12: Poisson traffic: delay vs. number of channels, with different P_{on}.

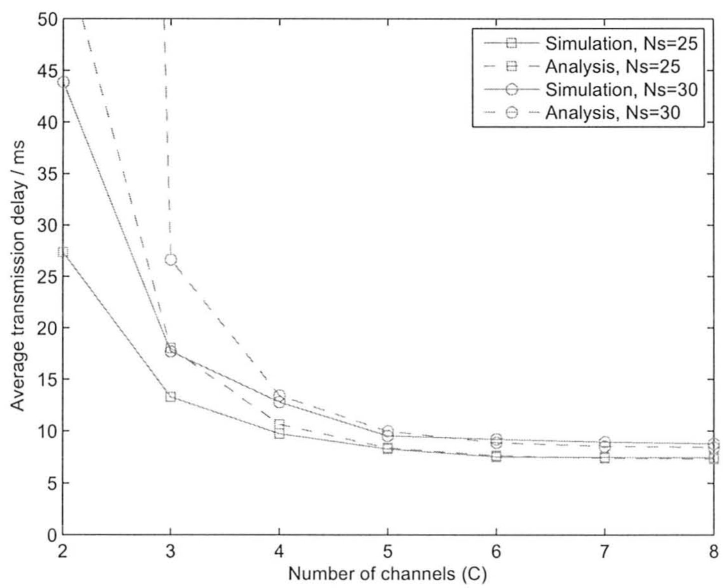


Figure 3.13: Poisson traffic: delay vs. number of channels, with different N_s.

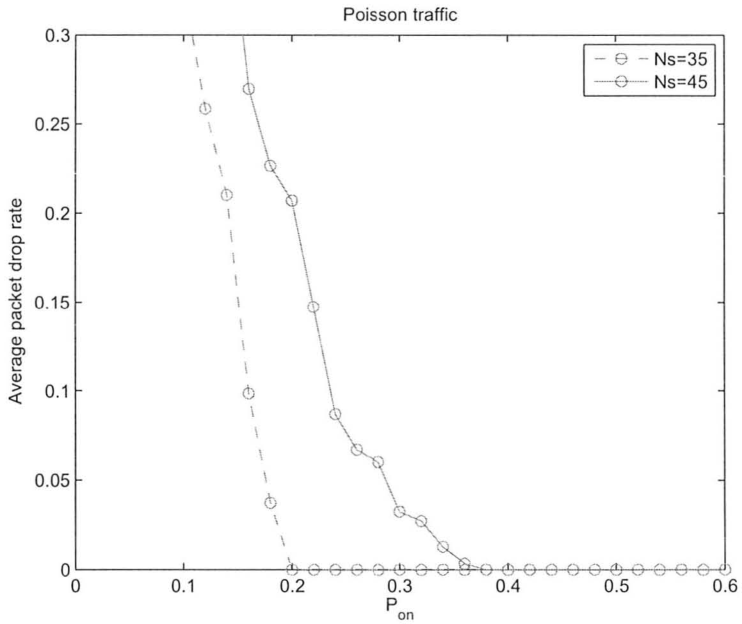


Figure 3.14: Poisson traffic: packet drop rate vs. P_{on}, with different N_s.

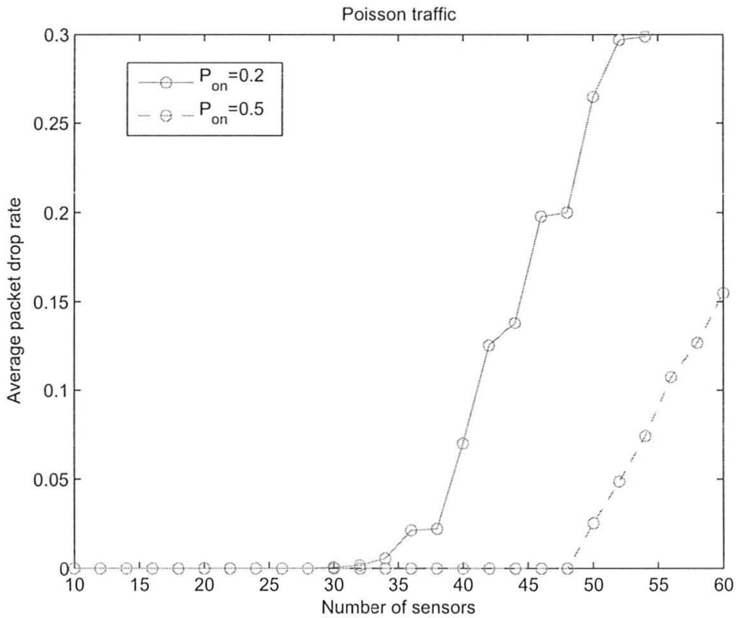


Figure 3.15: Poisson traffic: packet drop rate vs. number of sensors, with different P_{on}.

Chapter 4

Throughput Optimization

Having a large number of candidate channels for a cluster can increase the available channel time. Given the total number of candidate channels for a multi-cluster CRSN, how to allocate the channels among the clusters can be important in order to maximize the overall system throughput. In a multi-cluster CRSN, this is also related to the timeline allocations of the CHs for intra-cluster and inter-cluster traffic. Therefore, throughput maximization is a joint problem of channel and timeline allocations.

This problem is solved in two steps in this chapter. The first is to assume that the number of candidate channels assigned to each cluster is given, and find the optimum system throughput by allocating the timeline of each CH for local traffic, receiving from child CHs, and transmitting to the parent CH. The next step is to use a heuristic scheme to find the number of candidate channels assigned to each CH, so that to maximize the system throughput.

4.1 Problem Formulation

We consider a CRSN with the cluster tree topology, such as the example shown in Fig. 2.1. Define $T_{L,k}^{res}$, $T_{R,k}^{res}$ and $T_{T,k}^{res}$, respectively, as the reserved time at a level-k CH for local traffic, receiving from its child CHs, and transmitting to its parent CH in an SF, where $k = 0, 1, 2, \ldots, K$, and K is the total number of levels in the cluster tree excluding the sink, which is at level-0. Then we have

$$T_{L,k}^{res} + T_{R,k}^{res} + T_{T,k}^{res} \leq T_{SF}. \tag{4.1}$$

For special cases, $T_{T,0}^{res} = 0$ since the sink receives traffic only, and $T_{R,K}^{res} = 0$ since the level-K CHs do not have child CHs.

Let $T_{L,k}$, $T_{R,k}$ and $T_{T,k}$, respectively, be the available channel time in the reserved time intervals of a level-k CH for local traffic, receiving from its child CHs, and transmitting to the parent CH in an SF. Similar to equation (2.2) we have:

$$T_{L,k} = \frac{\overline{T}_{on}}{\overline{R}_k} T_{L,k}^{res}, \tag{4.2}$$

$$T_{R,k} = \frac{\overline{T}_{on}}{\overline{R}_k} T_{R,k}^{res}, \tag{4.3}$$

where $\overline{R}_k$ is the mean of renewal interval duration for a level-k CH and given by

$$\overline{R}_k = \overline{T}_{on} + \frac{\overline{T}_{off}}{C_k}(1 - P_{on})^{C_k}, \tag{4.4}$$

and C_k is the number of candidate channels assigned to a level-k CH, $k = 0, 1, 2, \ldots, K-1$.

Define N_k as the total number of level-k CHs, and C as the total number of candidate channels. We have

$$\sum_{k=0}^{K-1} C_k N_k \leq C. \tag{4.5}$$

Consider a homogeneous network, where all the level-k clusters have the same number of level-$k+1$ child clusters, then N_{k+1}/N_k is an integer. Since each level-k CH should receive from $\frac{N_{k+1}}{N_k}$ level-$k+1$ CHs, the following condition is necessary so that each of the level-$k+1$ child CHs can access its parent CH without competing with other CHs:

$$T_{R,k}^{res} \geq T_{T,k+1}^{res} \frac{N_{k+1}}{N_k}. \tag{4.6}$$

For each CH, the average amount of data collected from local sensors plus that received from child clusters equal the average amount of data that should be forwarded to the parent CH. Assume that one unit of available channel time achieves one unit of successfully transmitted data for inter-cluster communications; and η units, $0 < \eta < 1$, of successfully transmitted data for contention-based intra-cluster communications, then

$$T_{T,k} = T_{R,k} + \eta T_{L,k}. \tag{4.7}$$

The total throughput is a sum of the local throughput in all the clusters, and an optimization problem can be formulated as

$$\max \sum_{k=1}^{K} \eta T_{L,k} N_k \tag{4.8}$$

$$\text{s.t.} \quad T_{L,k}^{res} + T_{R,k}^{res} + T_{T,k}^{res} \leq T_{SF}, k = 0, 1, \ldots, K \tag{4.9}$$

$$T_{L,k} = \frac{\overline{T}_{on}}{\overline{R}_k} T_{L,k}^{res}, k = 1, \ldots, K \tag{4.10}$$

$$T_{R,k} = \frac{\overline{T}_{on}}{\overline{R}_k} T_{R,k}^{res}, k = 0, 1, \ldots, K-1 \tag{4.11}$$

$$T_{R,k}^{res} = T_{T,k+1}^{res} \frac{N_{k+1}}{N_k}, k = 0, 1, \ldots, K-1 \tag{4.12}$$

$$T_{T,k} = T_{R,k} + \eta T_{L,k}, k = 1, \ldots, K \tag{4.13}$$

$$\overline{R}_k = \overline{T}_{on} + \frac{\overline{T}_{off}}{C_k}(1 - P_{on})^{C_k}, k = 0, 1, \ldots, K-1 \tag{4.14}$$

$$\sum_{k=0}^{K-1} C_k N_k \leq C \tag{4.15}$$

$$T_{T,0} = 0 \tag{4.16}$$

$$T_{R,K} = 0 \tag{4.17}$$

4.2 Optimal Timeline Allocations

Given C_k's and $\overline{R}_k$'s, the optimization problem in the previous section becomes a linear problem, and $T_{L,k}^{res}$, $T_{L,k}$, $T_{R,k}^{res}$, $T_{R,k}$, $T_{T,k}^{res}$ and $T_{T,k}$ can be solved for all k. For different C_0's, we plot the total throughput of the network shown in Fig. 2.1 versus C_2 and C_3 in Fig. 4.1, where T_{SF} = 52ms, P_{on} = 0.1, and η=0.5. In the figure, each surface is the throughput for a given C_0. The surfaces from bottom to top stand for $C_0 = 1, 2, \ldots, 10$, respectively. It can be seen that in most part of each surface, C_1 and C_2 do not affect the total throughput. When C_0 is relatively small, increasing C_0 significantly improves the total throughput, since the available channel time at the sink is the capacity bottleneck of the network. When C_0 is large enough, further increasing it has limited effect on the system throughput, because the capacity is now limited by the available channel time at the level-1 and 2 CHs.

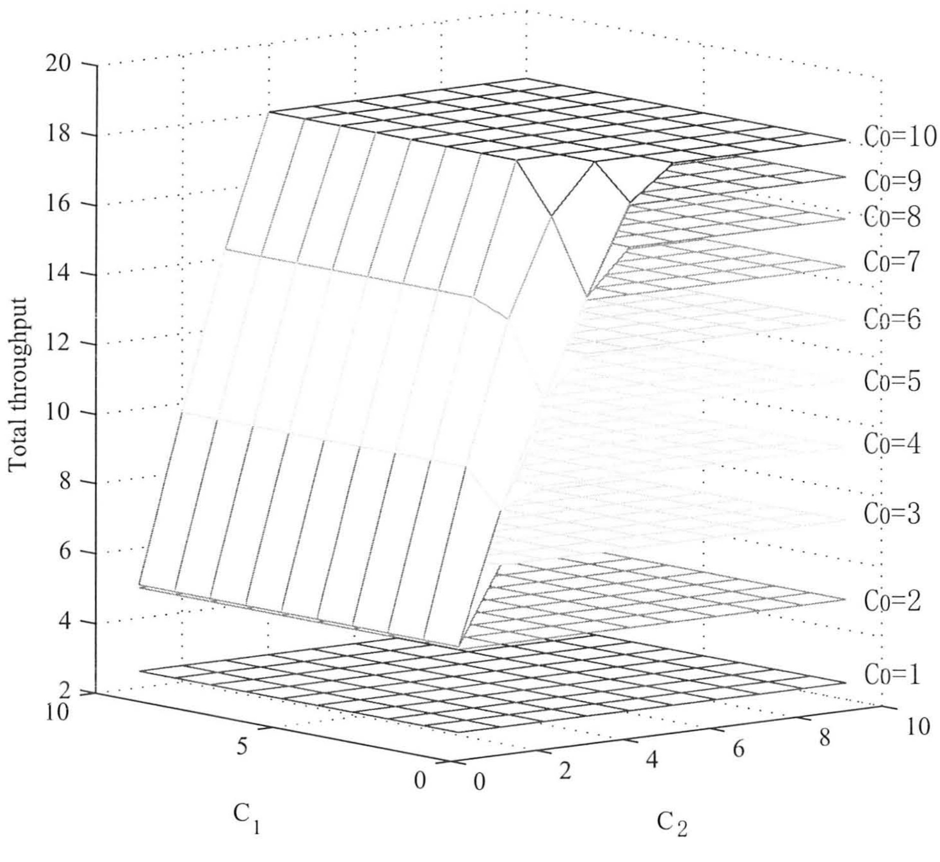


Figure 4.1: Exhaustive search: system throughput vs. number of channels. The surfaces from bottom to top stand for $C_0 = 1, 2, \ldots, 10$, respectively.

Table 4.1 shows the maximum system throughput that can be achieved for given C_0. For each C_0, we do exhaustive search for different values of C_1 and C_2 and find the maximum achievable throughput, which is shown in the last row of the table. When C_1 or C_2 is larger than certain values, increasing them does not increase the system throughput. Therefore, we also record the minimum values of C_1 and C_2 that result in the maximum throughput, and their values are listed in the second and third rows of the table. The fourth row is the total number of channels calculated using the left hand side of (4.5).

Next, we vary P_{on} to see its impact on the throughput. Fig. 4.2 shows the throughput surfaces for $P_{on} = 0.1$ and 0.5, respectively. When P_{on} is large the throughput solely depends on C_0, i.e. the capacity of the sink. In this case a small number of channels at the level-1 and 2 clusters are sufficient for achieving the maximum throughput. It can be found that, a cluster closer (in terms of number of hops) to the sink should be allocated more channels, since more traffic is carried by each higher-level CH.

C_0	2	2	4	4	7
C_1	1	2	2	3	4
C_2	1	1	1	1	1
total # of channels	8	10	13	14	19
total throughput	4.87	7.13	9.23	11.15	14.51
C_0	8	9	10	11	12
C_1	5	5	5	6	6
C_2	1	1	1	1	1
total # of channels	22	23	24	27	28
total throughput	16.99	17.07	18.04	19.38	19.75

Table 4.1: Exhaustive search: optimal channel allocations and corresponding throughput.

4.3 Optimum Channel Allocations

The previous section finds the optimum number of channels for the clusters at each level in order to maximize the total throughput. The exhaustive search method is

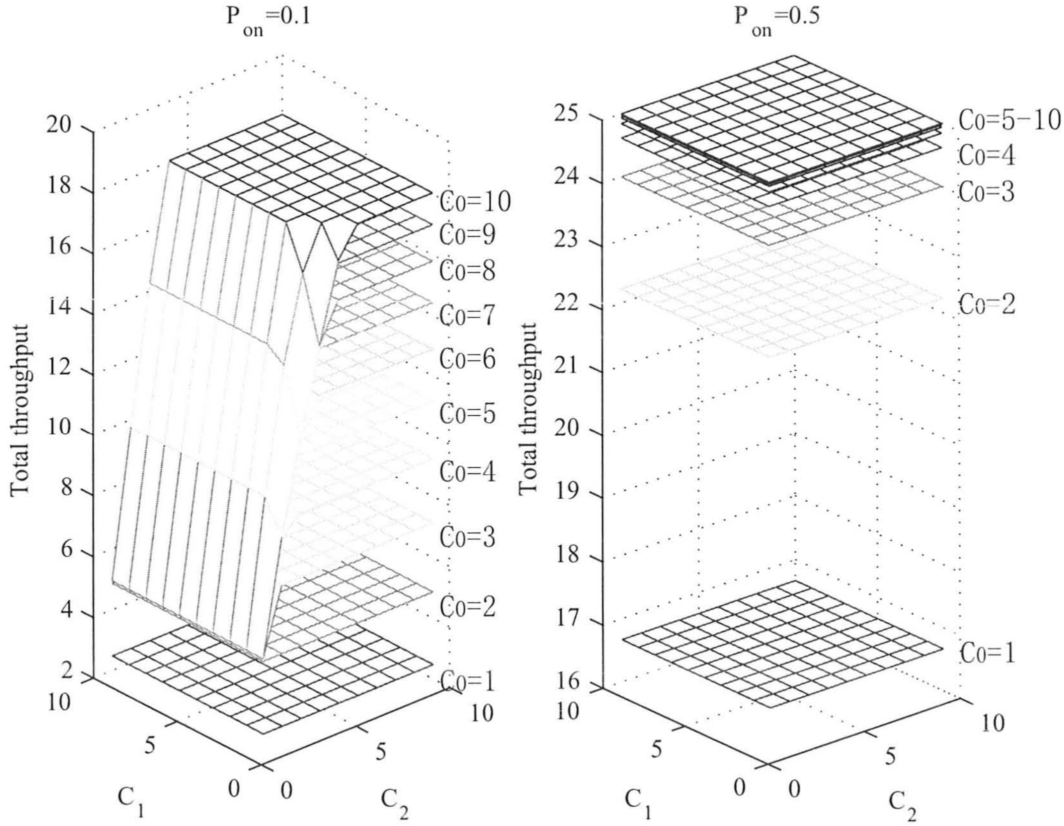


Figure 4.2: Exhaustive search: system throughput vs. number of channels for different P_{on}'s. The surfaces from bottom to top stand for $C_0 = 1, 2, \ldots, 10$, respectively.

not efficient and cannot be extended to large networks. In this section we design a heuristic scheme to achieve the same objective with much lower complexity, where C_total is the total number of channels allocated to all the clusters, and the optimal channel time allocations in lines 11 and 17 are obtained by solving the optimization problem in Section 4.2 with K replaced with $TOTAL\_LEVEL$.

The algorithm first assigns one channel to each CH. After finding the optimum time allocations, the level of CHs having the least amount of remaining time, $T_{rem} = T_{SF} - T_{L,k}^{res} - T_{T,k}^{res} - T_{R,k}^{res}$, is the capacity bottleneck. One more channel is allocated to each CH at the level, the optimum time allocation is recalculated. The process is repeated until all channels have been allocated, or the number of remaining channels is less than the number of bottleneck CHs.

Algorithm 1 Heuristic Channel Allocation Scheme

1: define constant TOTAL_CHANNEL; //total number of channels;
2: define constant TOTAL_LEVEL; // total number of levels;
3: define constant array N(0:TOTAL_LEVEL-1); // number of clusters in each level;
4: C_total = 0; // number of channels already assigned;
5:
6: **for** {k=0:TOTAL_LEVEL-1} **do**
7:    C(k) = 1; // number of channel assigned to each level-k cluster;
8: **end for**
9:
10: Update: C_total = $\sum_{k=0:TOTAL\_LEVEL-1} C(k)N(k)$;
11: Find optimal time allocations;
12:
13: **while** {C_total < TOTAL_CHANNEL} **do**
14:    $j = \arg\min_k (T_{SF} - T_{L,k}^{res} - T_{T,k}^{res} - T_{R,k}^{res})$;
15:    Update: C(j) = C(j) + 1;
16:    Update: C_total = $\sum_{k=0:TOTAL\_LEVEL-1} C(k)N(k)$;
17:    Find optimal time allocation using equations in section 4.2;
18: **end while**

Table 4.2 shows the maximum throughput using the heuristic algorithm. It can be seen by comparing Tables 4.1 and 4.2 that, given the same number of total channels, the heuristic algorithm achieves exactly the same throughput as the exhaustive search method.

total number of channels	8	10	13	14	19
total throughput	4.87	7.13	9.23	11.15	14.51
total number of channels	22	23	24	27	28
total throughput	16.99	17.07	18.04	19.38	19.75

Table 4.2: Heuristic algorithm: total number of channels and corresponding maximum throughput

The objective function in (4.8) maximizes the total throughput of all clusters without considering throughput of clusters at individual levels. The throughput of individual clusters is not considered in the heuristic scheme as well. While maximizing the total system throughput, both the optimization problem and the heuristic method may result in significantly unbalanced throughput for clusters at different levels. Table 4.3 shows the throughput of individual clusters at level-1 and level-2. It can be seen that a level-1 cluster has much higher throughput than a level-2 cluster since it takes one more hop for the traffic collected by the level-2 CHs to reach the sink than the traffic collected by the level-1 CHs, and it is more efficient to carry traffic in level-1 clusters from the perspective of maximizing the total throughput.

Total number of channels	8	10	13	14	19
Local throughput of each level-1 CH	1.86	2.61	3.99	3.12	3.95
Local throughput of each level-2 CH	0.28	0.48	0.31	1.23	1.65
Total number of channels	22	23	24	27	28
Local throughput of each level-1 CH	5.31	5.23	7.72	6.39	9.1
Local throughput of each level-2 CH	1.59	1.65	0.65	1.65	0.39

Table 4.3: Local throughput of clusters at different levels

Next we consider that the local throughput of clusters at individual levels is proportional to a weight, i.e.,

$$\frac{T_{L,k}}{T_{L,k'}} = \frac{w_k}{w_{k'}}, \tag{4.18}$$

for all $k, k' = 1, 2, \ldots, K$, where w_k is the weight for a level-k cluster, which can be the number of sensors in the cluster. When $w_k = 1$ for all $k = 1, 2, \ldots, K$, all the clusters have the same local throughput. Adding this constraint to the optimization problem in Section 4.2, the results of the optimum throughput for given total number of channels using the exhaustive search method and the heuristic scheme are shown in Tables 4.4 and 4.5, respectively. Comparing these results with the ones shown in Table 4.2 we can see that more channels are required for the case with fair throughput requirement in order to achieve the same total throughput.

C_0	2	2	4	4	5
C_1	1	2	2	3	3
C_2	1	1	1	1	2
Total # of channels	8	10	13	14	19
Total throughput	4.25	4.87	8.35	9.23	11.15
C_0	6	7	8	9	10
C_1	4	4	4	5	5
C_2	2	2	2	2	2
Total # of channels	22	23	24	27	28
Total throughput	12.88	14.42	15.79	16.99	18.04

Table 4.4: Exhaustive search: optimal channel allocations and corresponding throughput, with equal local throughput requirements.

Total number of channels	8	10	13	14	19
Total throughput	4.25	4.87	8.35	9.23	11.15
Total number of channels	22	23	24	27	28
Total throughput	12.88	14.42	15.79	16.99	18.04

Table 4.5: Heuristic algorithm: total number of channels and corresponding maximum throughput, with equal local throughput requirements.

Chapter 5

Summary and Future Work

We have studied a wireless sensor network that accesses vacant channels in the licensed spectrum in this thesis. Delay and packet drop rate performance for the real-time traffic and throughput performance for the best effort data traffic are considered. Our results indicate that satisfactory performance, including both the average packet transmission delay and packet drop rate, can be provided for the real-time traffic in the network. In general, Poisson traffic may experience shorter delay than the bursty traffic. We have also studied throughput maximization for the best effort traffic through allocating timelines of individual CHs and the candidate channels among clusters.

Given the complicated distribution of the channel available time, the analytical models were only derived for the average packet transmission delay. In the future, we will consider to develop analytical models for the packet drop rate performance, and the capacity for the real-time traffic will be found based on the delay performance requirements. We may also extend the analysis for the real-time traffic in a multi-hop environment, where the CHs can forward data collected from directly associated sensors to the sink via a small number of hops. QoS of the real-time traffic will also be considered when allocating candidate channels among multiple clusters in order to maximize the real-time traffic capacity. We will also consider the possibility that different clusters can share the same candidate channels. Intuitively, sharing the candidate channels may improve the resource utilization. On the other hand, it may result in that neighboring clusters compete for the same available channel and reduce the overall throughput.

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