Delay Performance for Supporting Real-time Traffic in a Cognitive Radio Sensor Network

DELAY PERFORMANCE FOR SUPPORTING REAL-TIME TRAFFIC IN A COGNITIVE RADIO SENSOR NETWORK

BY

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Abstract

Traditional wireless sensor networks (WSNs) working in the license-free spectrum suffer from uncontrolled interference as the license-free spectrum becomes increasingly crowded. Designing a WSN based on cognitive radio can be promising in the near future in order to provide data transmissions with quality of service requirements. In this thesis, we introduce a cognitive radio sensor network (CRSN) and analyze its performance for supporting real-time traffic. The network devices opportunistically access vacant (or available) channels in the licensed spectrum. When the current channel becomes unavailable, the devices can switch to a new channel.

Three types of real-time traffic are considered, constant-bit-rate (CBR) traffic, bursty traffic, and Poisson traffic. For the CBR traffic, a fixed number of packets are generated periodically; for the bursty traffic, a burst of packets are generated periodically and the number of packets in each burst is random; and for the Poisson traffic, the packet arrivals follow Poisson process. We derive the average packet transmission delay for each type of the traffic. The analytical results are verified by computer simulations. Our results indicate that real-time traffic can be effectively supported in the CRSN, and packets with the Poisson arrivals may experience longer average delay than the bursty arrivals.

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Abbreviations

ACK Acknowledgment

BE Best Effort

CAP Contention Access Period

CBR Constant-bit-rate

CFP Contention Free Period

CH Cluster Head

CR Cognitive Radio

CRN Cognitive Radio Network

CRSN Cognitive Radio Sensor Network

CS Channel Switching

CSMA-CA Carrier Sense Multiple Access with Collision Avoidance

CTS Clear to Send

FCC Federal Communications Commission

GTS Guaranteed Time Slot

ISM The Industrial, Scientific and Medical

LR-WPAN Low-Rate Wireless Personal Area Network

MAC Medium Access Control

PAN Personal Area Network

PHY Physical Layer

PST Packet Service Time

QoS Quality of Service

RTS Request to Send

WLAN Wireless Local Area Network

WPAN Wireless Personal Area Network

WSN Wireless Sensor Network

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Chapter 1

Introduction

1.1 Introduction to Wireless Sensor Networks

1.1.1 Overview of Wireless Sensor Networks

Recent advances in wireless networking and electronics have significantly improved the development of wireless sensor networks (WSNs), which are designed to provide low-cost, low-power and multi-functional applications and interact with the physical environment [1], [2]. WSNs have been widely used in both industrial and civilian areas, such as in environmental monitoring, industrial process management, traffic control, home automation, health care monitoring and so on [3], [4]. A WSN is composed of a large number of spatially distributed devices, which can be deployed in star or peer-to-peer topology [5], [6]. A WSN can have one or multiple data sinks, which are responsible for sending query to and collecting data from the regular sensors.

Sensors are the most basic components in a WSN and used for gathering and disseminating collected information to designated sinks for further processing. A sensor is usually equipped with a micro-processor, radio transceivers, a sensing unit and a memory unit. Sensors are usually very small in size and powered by batteries, which are not rechargeable in most applications.

A single sensor can be very small and have very limited capacity for collecting data. In order for a WSN to cover a very large area and provide a rich and multi-dimensional view of the environment, a large number of sensors may have to be deployed. Data collected by a sensor may need multiple hops before reaching the sink. In a cluster-based WSN, sensors are divided into clusters with a cluster head (CH) in each cluster. Data collected by the sensors are first sent to the nearby CHs, which further forward the data to the sink via one or multiple hops through other CHs. Fig. 1.1 shows an example of a cluster-based WSN. In order to transport both intra-cluster and inter-cluster traffic, energy consumption of a CH can be much higher than that of a regular sensor. The CHs can be regular sensors, in which case the sensors take turns to be the CHs in order to balance the energy consumptions. As a result, the network topology changes dynamically from time to time. Alternatively, the CHs can be specially designed nodes, and this results in relatively static network topology. The CHs together with the sinks form a relatively stable wireless infrastructure, making it possible for transmitting data with certain quality of service (QoS) guarantee.

It is essential for WSNs to provide data transmissions with strict QoS in various applications, such as industrial monitoring, traffic control and so on, in which high latency, high packet loss rate or other problems cannot be accepted. Besides, in many applications, 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

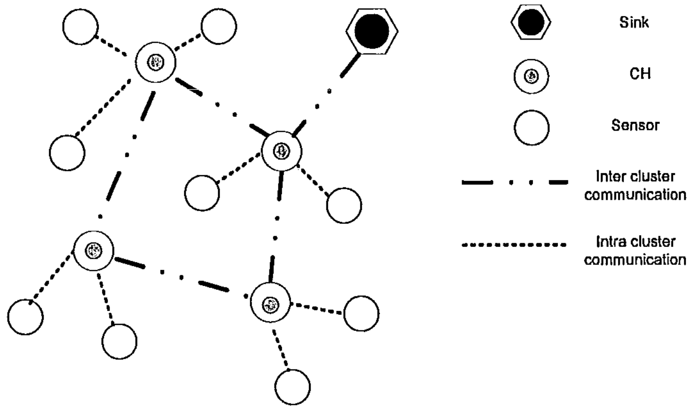

Figure 1.1: Illustration of a wireless sensor network

of a patient should reach the doctor as soon as possible [7], [8]; in environmental monitoring, a wireless smoke sensor should provide real-time recognition of smoke or fire [9]. As a result, guaranteeing QoS of different types of traffic is becoming a key issue in future WSNs.

1.1.2 Standards for Wireless Sensor Networks

The WPAN Working Group created IEEE 802.15.4 Low-Rate WPAN (LR-WPAN) standard [10], which focuses on defining the physical layer (PHY) and medium access control (MAC) sublayer specifications for low-cost, low-energy, and low-complexity wireless networks. In order to provide a more complete networking solution, ZigBee Alliance [11], an independent, open and non-profit corporation, developed network and application layers specifications, which have not been covered by IEEE 802.15.4. IEEE 802.15.4 combined with ZigBee is widely considered as one of the most promising standards suitable for WSNs.

According to the IEEE 802.15.4 standard, sensors are able to operate in three license free industrial, scientific, and medical (ISM) radio bands in 868 MHz (Europe), 915 MHz (America), and 2.4 GHz (worldwide). A low-band PHY operating contains 1 channel in the 868 MHz band and 10 channels in the 915 MHz band, and has a raw data rate of 20 kbps and 40 kbps, respectively. A high-band PHY operating in the 2.4 GHz band has 16 channels. It specifies a data rate of 250 kbps and has nearly worldwide availability [12]. The 2.4 GHz frequency band has the most potential uses for large-scale WSN applications, since the high data rate reduces the frame transmission time and thus the energy consumption per transmitted and received bit.

Beacons are used in the IEEE 802.15.4-based network to synchronize the attached devices and to describe the structure of the superframe. The superframe is bounded by network beacons and divided into 16 equally sized time slots [13]. The IEEE 802.15.4 standard allows the optimal use of a superframe structure, which can have an active and an inactive portion. The active portion of each superframe is composed of three parts: a beacon, a contention access period (CAP) and a contention free period (CFP). The beacon is transmitted, without the use of carrier sense multiple access with collision avoidance (CSMA-CA), at slot 0, and the CAP commences immediately after the beacon. Devices wishing to communicate during the CAP between two beacons compete with each other using a slotted CSMA-CA mechanism. The CFP, if present, follows immediately after the CAP and extends to the end of the active portion of the superframe.

ZigBee Alliance defines three network topologies above the IEEE 802.15.4 physical and MAC layers, the cluster-tree topology, the star topology and the mesh topology [14]. Both the star and cluster-tree topologies can use beacon frames to synchronize devices to their parent node, and thus minimize power consumption of the devices by intermittent operations. The cluster-tree topology has a better scalability than the star topology and is more suitable for large-scale sensor networks. As a result, the cluster-tree topology is attracting increasingly more attention recently, e.g., [15], [16] and [17].

1.2 Wireless Sensor Networks Based on Cognitive Radio

Most current WSNs work under IEEE 802.15.4 standard and operate in the license-free bands. One of the most outstanding advantages of using the license-free bands is the flexibility and low cost. Small business and household are able to implement the networks without applying for licensed spectrum, and the WSNs can be deployed anywhere as needed. However, utilizing the license-free bands also induces problems. Since the license-free frequency bands are an open resource, other wireless networks can also work in the same spectrum, and all of the users in the different networks may have to share this resource at the same time and in the same geographical area. Currently, the license-free spectrum has been crowded by IEEE 802.11-based WLANs, IEEE 802.15-based Wireless Body Area Networks (WBANs), and IEEE 802.16-based WiMAX networks. Transmissions in the license-free bands can experience interference from other networks sharing the same spectrum, making it very difficult to predict the quality of service (QoS). The coexistence of multiple networks in the same license-free spectrum also brings challenging issues [18] including spectrum utilization, security, transmission collisions and other issues between the same or different wireless technologies, posing a major problem for supporting traffic with strict QoS requirements.

Assessment of the coexistence problems has been studied extensively, such as in [19] and [20].

Furthermore, the coexistence of multiple networks in the license-free bands has worse impact on WSNs than other networks due to the special properties of the WSNs as shown in [21] and [22]. For example, a WSN based on IEEE 802.15.4 may operate in the presence of an IEEE 802.11-based wireless local area network (WLAN) [23], and channels of the WSN may overlap channels of WLAN so that interference affects users in both networks. Since transmission power in the WSN is usually much lower than in the WLAN, the interference caused by the coexistence of the two networks impacts the WSN more seriously. As a result, data transmission performance in a WSN can be significantly deteriorated. As the license-free spectrum becomes increasingly crowded, traditional WSNs operating on the license-free bands are expected to suffer from heavy interference caused by other networks sharing the same spectrum [24], [25], and therefore are not suitable for supporting traffic with strict QoS requirements.

There has been some work that studies the coexistence problem in order to provide better performance in WSNs. In [26], the packet error rate of a WSN coexisting with other networks is analyzed. In [27], the IEEE 802.15.4 channel occupancy pattern in presence of WLANs is studied, and the work provides a better understanding of the interference caused by coexistence between these two standards. The authors of [28] proposed to reduce interference by using energy detection-based measurements conducted by sensors. All these efforts can help understand or reduce the effect of interference to the WSNs caused by other networks coexisting in the same spectrum band, but they do not provide solutions for providing services with QoS requirements in WSNs.

Building a WSN based on cognitive radio can be a promising approach in the future in order to avoid issues caused by coexistence of multiple networks in the license free spectrum. The low spectrum utilization in the licensed spectrum leaves a large amount of resources for the WSNs to serve traffic with strict QoS requirements. Without having to access dedicated licensed spectrum, it is possible to build WSNs with a low cost. Another major advantage of combining wireless sensor networking with the cognitive radio technology is the flexibility. There is little restriction on the air interfaces, coverage area and network topologies. 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.

Due to these great advantages, there has been some recent work in cognitive radio-based sensor networks (CRSNs). Some general implementation issues are discussed in [29],[30] and [31]. Possible implementations of a CRSN is presented in [32] from a system level point of view. In [33] a conceptual design of cognitive radio-based sensor networks is proposed, where some advantages and challenges are discussed. In [34], performance of a CRSN for supporting health care traffic is studied. Energy efficiency in a CRSN with multi-carrier modulation is studied in [35] and [36]. On the other hand, little work has been done on supporting real-time traffic in CRSNs. Next, we give a brief overview for cognitive radio networks in Section 1.3 before introducing the work of this thesis in Section 1.4.

1.3 Related Works in Cognitive Radio Networks

With the successful development of wireless networks in the last decades, the demand for wireless communications has significantly increased. The limited radio spectrum assigned by the traditional fixed spectrum allocation method cannot afford such high growing demands. Considering that bandwidth demands may vary highly along the time and space dimension, a lot of spectrum that has been allocated to various networks may be under-utilized [37], leaving a large amount of idle resources. Therefore, there is huge potential to increase the efficiency of spectrum usage [38].

Cognitive radio (CR) is a technology that helps fully utilize the scarce radio spectrum resources, while satisfying the increasing demands for wireless communications. With the development of CR technologies, the Federal Communications Commission (FCC) [39] in the United States allows unlicensed wireless users (secondary users) to dynamically access the licensed bands from legacy spectrum holders (primary users) on a negotiated or an opportunistic basis [40], [41]. A good survey regarding problems and solutions for cognitive radio networks (CRNs) can be found in [42] and the references therein.

The basic function of CR is spectrum management [43], which contains spectrum sensing, spectrum decision and spectrum sharing. Spectrum sensing is to detect unused spectrum and share the resource with other users in the secondary networks without harmful interference [44]. The detection methods for spectrum sensing can be divided into several categories, such as transmitter detection, cooperative detection and interference detection, and many detection algorithms have been investigated in the literature [45]. After spectrum sensing, it is necessary to implementing spectrum decision and spectrum sharing functions. The purpose of spectrum decision is to select the best unused spectrum based on spectrum availability to meet users' requirements, and spectrum sharing is used for coordinating access demands among different users in the secondary networks.

Depending on the dynamics of spectrum usage in the primary networks, users in the secondary networks may have to change their transmission parameters frequently. Providing guaranteed QoS for various traffic in such an environment can be different from that in traditional wireless networks. Recently, some work has been done on supporting traffic with QoS in CRNs. For example, performance for transmitting voice traffic in a CRN is studied in [46], [47], where a single channel is shared by the CRN and the primary network. Capacity of VoIP traffic in a CRN with imperfect spectrum sensing is studied in [48]. Other works studying real-time performance for traffic in CRNs can be found in [49], [50].

1.4 Overview of The Thesis

In this thesis we study the performance of supporting real-time traffic in a CRSN, where devices opportunistically access available channels in the licensed spectrum. The MAC protocol is compatible with the IEEE 802.15.4 protocol, which is one of the most popular standards for WSNs. The network is cluster-based. Sensors communicate directly with their associated cluster heads (CHs), which perform spectrum sensing and inform the sensors about the channel availability. We consider three types of real-time traffic, i) a fixed number of packets are generated periodically, ii) a burst of packets are generated periodically and the number of packets in each burst is random, and ii) packet arrivals follow a Poisson process. For each type of the traffic, we derive the average packet transmission delay. We also consider best effort (BE) traffic which uses the radio resources remaining from serving the real-time traffic, and derive the available service time the BE traffic. Capacity of the network is also derived.

The remainder of the thesis is organized as follows. In Chapter 2, we give a general description of the CRSN, including network topology, channel sensing mechanism, and radio resource allocations. We also find the distribution of available channel time in the network. The amount of available service time for the BE traffic and the network capacity are also derived in the chapter. In Chapter 3, analytical models are derived for analyzing the average delay for serving the real-time traffic. Numerical results are shown in Chapter 4 to demonstrate the performance of the network, and computer simulation results are used to verify correctness of the analysis. Chapter 5 concludes the thesis.

Chapter 2

Description of a CRSN

In this chapter, we first introduce the CRSN, including the basic network architecture, channel sensing and switching, and channel time allocations. We then find the distribution of available channel time, and based on this, system capacity in terms of the maximum number of sensors that can be supported is derived. Finally, the available service time for the BE traffic is derived.

2.1 Network Architecture

The IEEE 802.15.4 standard defines the PHY and MAC layers for low-rate, low-power and flexible wireless personal area networks. It allows two types of contention-based channel access mechanisms: a slotted CSMA/CA used in the beacon enabled network, and an unslotted CSMA/CA used in the non-beacon enabled network. For the former, a superframe is defined to be the period between two successive beacons. Beside the contention-based period, contention free transmissions are also allowed, providing much higher efficiency.

Sensors in the CRSN are grouped into clusters and communicate directly with their associated cluster heads (CHs). In addition to collecting data from the sensors, the CHs are also responsible for sensing available channels from a number of frequency channels in a licensed band, allocating radio resources, and sending control signals to the sensors. In a CRSN, data transmissions are mainly from the sensors to the CHs, and transmissions from the CHs to the sensors are mainly for sending acknowledgment (ACK) frames, channel allocation messages, and other control signaling messages. The real-time traffic collected by a CH can be processed locally if the CH is co-located with the data sink. Such a single-hop scenario can be very common for real-time traffic due to the strict latency requirement. Alternatively, the data may be further forwarded by the CH to a remote data sink through traditional communication networks, such as a wireline communication network or a high-speed wireless communication network such as an IEEE 802.16-based wireless metropolitan area network. In such cases, data transmission delay beyond the CH is usually much smaller, compared to that between the sensors and the CH, and can be neglected. Therefore, this work focuses on transmission delay between the sensors and the CH within a cluster.

A common control channel is used for the CH to notify the sensors about the current available channels. All sensors listen to the common control channel at the beginning of each CS interval. The CH broadcasts channel information through the control channel so that sensors can hear this message. If a new channel is available, the CH and the sensors then switch to the new channel. Selecting the common control channel requires coordinations between the sensors and the CH and this is discussed in [34].

2.2 Channel Switching

The CRSN opportunistically accesses frequency channels in a licensed spectrum. When a frequency channel is not used by the primary network, it is "available" for the CRSN. Once a channel is occupied by the primary network, it becomes "unavailable" to the CRSN.

The system time is divided into equal length intervals, referred to as channel switching (CS) intervals. If the current working channel becomes unavailable before the end of the CS interval, the CH simply waits until the start of the next CS interval, when it informs the sensors another available channel (if there is at least one available) and then both the CH and the sensors switch to the new channel. Sensors can simply go to a power saving mode once they detect a channel loss, and do not have to be active until the beginning of the next CS interval. This simplifies the synchronization between the sensors and the CH. It is also possible that the CH senses for new channels as soon as the previous channel is lost, and this helps the CRSN find more available channel time at the price of more complicated synchronization between the sensors and the CH. This is studied in [51]. When the traffic load is relatively low and capacity is not a concern, restricting the channel switchings to be at the beginning of the CS intervals can be a better choice.

Each cluster requires only one available frequency channel. The CH keeps sensing the frequency channels until an available channel is found or it finds that no channel is available. The total amount 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 being 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 at least one channel available after the previous channel is lost. In case the CH is only equipped with one radio, channel sensing is done before data communications, and T_{sw} includes not only the time for channel switching, but also the time for channel sensing. In such a case, the number of 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 [52]. Therefore, the value of T_{sw} should be much smaller than the amount of time for data communications.

2.3 Detecting a Channel Loss

We assume that the status change of a channel from being available to unavailable can be realized by the CH immediately. However, it may take time for the regular sensors to be informed of the channel loss. Therefore, it is possible that the sensors transmit at a channel, which is occupied by the primary network already. In this case, the transmissions from the sensors interfere that in the primary network, and this should be avoided as much as possible.

When the CH loses its channel, it stops broadcasting the beacons, and its associated sensors realize the channel loss in the next scheduled beacon time or earlier and stop their transmissions. There can be multiple beacons in each CS interval. Having more beacons can help the sensors know the availability of the current channel in time and reduce unnecessary transmissions. This also reduces interference to the primary network.

For reliable transmissions, 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 interference to the primary network.

2.4 Traffic and Resource Allocations

Both real-time traffic and best effort (BE) data traffic can be served. The real-time traffic is given a higher priority in order to satisfy its delay requirements, and its performance should not be affected by the transmissions of the BE traffic.

We adopt the IEEE 802.15.4 MAC protocol, which is commonly used for WSNs and specifies both contention-based and contention free transmissions. In order to achieve small transmission delay, the real-time traffic is served with contention-free transmissions using the guaranteed time slots (GTSs), and the BE traffic is served using the contention access period (CAP). Since an available channel can be lost during a CS interval and the sensors only switch to a new channel at the beginning of the CS intervals, they have a better chance to transmit at earlier time during each CS interval. Therefore, in each CS interval earlier time should be reserved for the real-time traffic. On the other hand, we find that in the IEEE 802.15.4 MAC protocol, each MAC superframe starts with a CAP which is then followed by GTSs. In order to have the CRSN fit into the IEEE 802.15.4 MAC, we can have the timelines of the

MAC superframes and the CS intervals carefully arranged so that the real-time service time is in the GTS periods of the MAC superframe and the earlier portion of the CS interval, and the BE service time is in the CAP interval in the MAC superframe and the later portion of the CS interval. An example of such timeline arrangement is shown in Fig. 2.1 with $T_{CS} = T_{SF}$, where T_{CS} and T_{SF} are the durations of a CS interval and a superframe, respectively. More examples can be found in Fig. 2.2 and Fig. 2.3 when $T_{CS} \neq T_{SF}$.

During the GTS period, an amount of T_r time is reserved for the real-time traffic. Note that the actual amount of available channel time for serving the real-time traffic in the reserved time interval is random due to the random channel availability, and its distribution will be derived in the next section. Channel time not reserved for the real-time traffic can be used for the BE traffic, and the available service time for the BE traffic is derived in Section 2.7

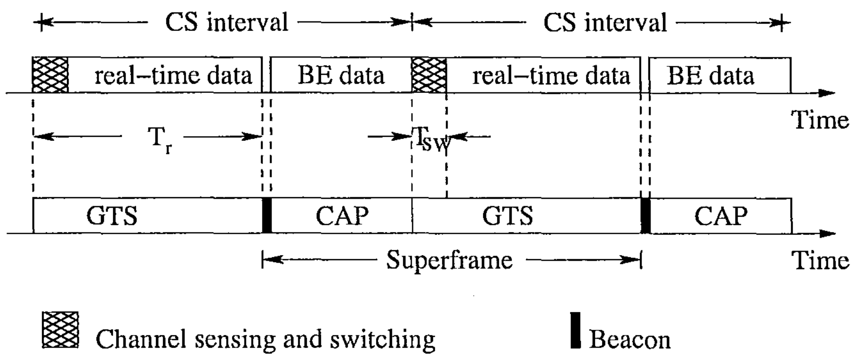

Figure 2.1: Time relation between MAC superframes vs. CS intervals, $T_{CS} = T_{SF}$

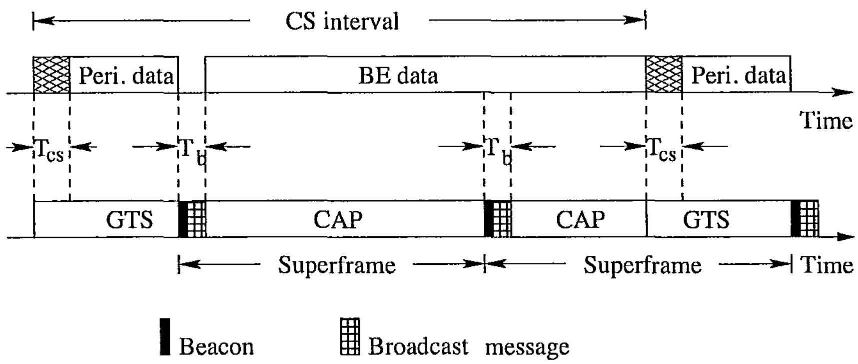

Figure 2.2: Time relation between MAC superframes vs. CS intervals, $T_{CS} = 2T_{SF}$

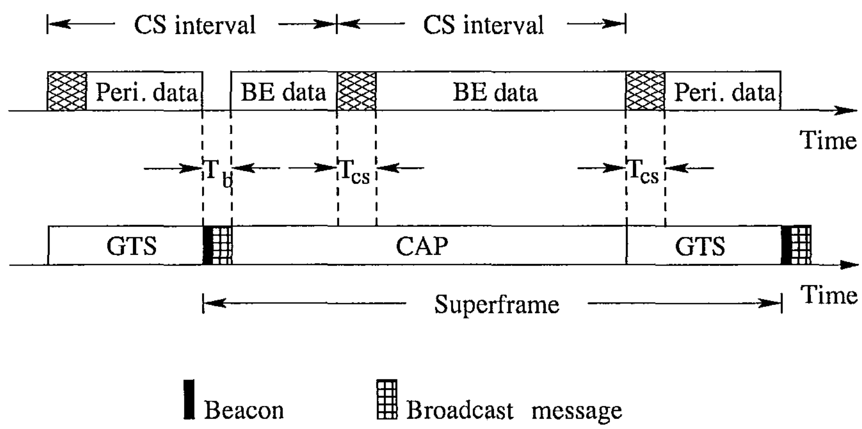

Figure 2.3: Time relation between MAC superframes vs. CS intervals, $2T_{CS} = T_{SF}$

2.5 Distribution of Channel Available Time

The amount of available channel time for the CRSN is random. In this section, we derive the distribution of the available channel time for the real-time traffic during the reserved time interval of duration T_r.

For a given frequency channel, we define a channel available interval, T_{on}, as a continuous interval during which there is no primary transmission activity, and a channel unavailable interval, T_{off}, during which the channel is always occupied by the primary transmissions. Both T_{on} and T_{off} are assumed to be 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 to the CRSN. Given that there are N channels in total, the probability of outage is $P_{out} = (1 - P_{on})^N$ when all the N channels are unavailable. We consider that all the frequency channels have the same statistical activities. That is, they all have the same distribution for their channel available intervals and the same distribution for their channel unavailable intervals. Furthermore, the available intervals of different channels are independent of each other.

We use T_a to denote the amount of available channel time during the reserved interval for the real-time traffic in a CS interval. Below we derive the distribution of T_a. When all the channels are unavailable, $T_a = 0$. That is,

$$\Pr.\{T_a = 0\} = P_{out}. \tag{2.1}$$

If there is at least one channel available and $T_{on} < T_r$, then $T_a = T_{on}$. For any

$0 < t < T_r$ we have

$$\Pr.\{T_a \leq t\} = P_{out} + (1 - P_{out})\Pr.\{T_{on} \leq t\} = P_{out} + (1 - P_{out})\left(1 - e^{-\frac{t}{\overline{T}_{on}}}\right). \quad (2.2)$$

If there is at least one channel available and $T_{on} \geq T_r$, then $T_a = T_r$. In this case,

$$\Pr.\{T_a = T_r\} = (1 - P_{out})\Pr.\{T_{on} \geq T_r\} = (1 - P_{out})e^{-\frac{T_r}{\overline{T}_{on}}}. \quad (2.3)$$

2.6 System Capacity

Replacing T_r in (2.2) and (2.3) with T_{CS}, we can find distribution of the amount of available channel time in a CS interval. Let $\overline{T}_{a,CS}$ be the average amount of available channel time in a CS interval. We have

$$\begin{aligned}
\overline{T}_{a,CS} &= (1 - P_{out})T_{CS}\Pr.\{T_{on} \geq T_{CS}\} + (1 - P_{out})\mathrm{E}[T_{on}|0 < T_{on} < T_{CS}] \\
&= (1 - P_{out})T_{CS}\int_{t=T_{CS}}^{\infty} \frac{1}{\overline{T}_{on}} e^{-\frac{t}{\overline{T}_{on}}} dt + (1 - P_{out})\int_{t=0}^{T_{CS}} \frac{t}{\overline{T}_{on}} e^{-\frac{t}{\overline{T}_{on}}} dt \\
&= (1 - P_{out})\overline{T}_{on}(1 - e^{-\frac{T_{CS}}{\overline{T}_{on}}}). \quad (2.4)
\end{aligned}$$

Let M_0 be the average number of packets that each sensor generates in every CS interval. The maximum number of sensors that can be supported in the reserved duration is given by

$$N_{\max} = \frac{\overline{T}_{a,CS}}{T_d M_0}. \quad (2.5)$$

2.7 Available Service Time for BE Traffic

After a period of T_r time is reserved for the real-time traffic in each CS interval, the rest of the CS interval can be used for transmitting BE traffic. Therefore, the available service time for the BE traffic is $T_a - T_r$ if $T_r < T_a < T_{CS}$, or $T_{CS} - T_r$ if $T_a \geq T_{CS}$. Define T_{be} as average available service time for the BE traffic. We have

$$\begin{aligned} T_{be} &= (1 - P_{out}) \left[\int_{t=T_r}^{T_{CS}} (t - T_r) \frac{1}{\overline{T}_{on}} e^{-\frac{t}{\overline{T}_{on}}} dt + (T_{CS} - T_r) \int_{t=T_{CS}}^{\infty} \frac{1}{\overline{T}_{on}} e^{-\frac{t}{\overline{T}_{on}}} dt \right] \\ &= (1 - P_{out}) \overline{T}_{on} (e^{-\frac{T_r}{\overline{T}_{on}}} - e^{-\frac{T_{CS}}{\overline{T}_{on}}}). \end{aligned} \tag{2.6}$$

Chapter 3

Delay Performance Analysis for Real-Time Traffic

Three types of real-time traffic are considered, constant-bit-rate (CBR) traffic, bursty traffic and Poisson traffic. For the CBR traffic, a fixed number of packets are generated periodically; for the bursty traffic, a burst of packets are generated periodically and the number of packets in each burst is random; and for the Poisson traffic, packet arrivals follow a Poisson process. The average packet transmission delay for the CBR traffic is derived in Section 3.1, for the bursty traffic is in Section 3.2 and for the Poisson traffic is in Section 3.3.

3.1 Delay Analysis for CBR Traffic

We consider that m packets are generated from the sensors at the same time right after the beginning of each CS interval [1], where m is a constant. In a practical

[1] Other cases when packets are generated at different and deterministic time instants can be derived similarly.

system, each sensor may generate one packet in every J CS intervals, where J can be much larger than 1, and m represents the total number of packets generated by all the sensors in a CS interval. We assume that all the packets are stored in a virtual buffer until they are transmitted to the CH, 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 deterministic, 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 CS interval. 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 CS interval only depends on its value at the end of the previous CS interval and the packet arrivals and channel availability in the current CS interval, 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 time caused by channel being unavailable. Channel time is divided into equal length time slots each with duration of T_d. Assuming that both T_{CS} and T_r are integer multiples of T_d, $K_{\max} = \frac{T_{CS}}{T_d}$ gives the total number of time slots in a CS interval, and $K = \frac{T_r}{T_d}$ is the number of time slots in the reserved interval for the real-time traffic. We further define p_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. Define

$p_k = 0$ for $k < 0$ or $k > K$. Given the distribution of T_a, we can find p_k as

$$p_k = \begin{cases} \Pr.\{T_a < T_d\}, & \text{if } k = 0, \\ \Pr.\{kT_d \leq T_a < (k+1)T_d\}, & \text{if } 1 \leq k < K, \\ \Pr.\{T_a = KT_d\}, & k = K, \end{cases} \tag{3.1}$$

$$= \begin{cases} P_{out} + (1 - P_{out})(1 - e^{-\frac{T_d}{T_{on}}}), & \text{if } k = 0, \\ (1 - P_{out})[e^{-\frac{kT_d}{T_{on}}} - e^{-\frac{(k+1)T_d}{T_{on}}}], & \text{if } 1 \leq k < K, \\ (1 - P_{out})e^{-\frac{T_r}{T_{on}}}, & k = K. \end{cases} \tag{3.2}$$

The state transition probability of X can be found as

$$Q_{ij} = \begin{cases} \sum_{k=i+m}^{K} p_k, & \text{if } j = 0 \text{ and } i + m \leq K, \\ p_{i+m-j}, & \text{if } i + m - K \leq j \leq i + m \text{ and } i + m > K, \\ 0, & \text{otherwise.} \end{cases} \tag{3.3}$$

Note that the state transition matrix, $Q = [Q_{ij}]$, based on the above derivation assumes an infinite buffer size, i.e., X can take any value from zero to infinity, and therefore, the dimension of the matrix is infinite. Thus, solving the steady state probability of X based on the above transition probability is very difficult.

Having a finite buffer size can simplify the problem. Let B represent the buffer size, then $0 \leq X \leq B$. Packets can be lost when the buffer is full. However, as long as B is much larger than K, the packet loss rate can be very small and neglected. In this case, the state transition probability of X can be written as

$$Q_{ij} = \begin{cases} \sum_{k=i+m}^{K} p_k, & \text{if } j = 0 \text{ and } i+m \leq K, \\ p_{i+m-j}, & \text{if } i+m-K \leq j \leq i+m \text{ and } K < i+m \leq B \\ p_{B-j}, & \text{if } B-K \leq j \leq B \text{ and } i+m > B,, \\ 0, & \text{otherwise.} \end{cases} \tag{3.4}$$

Define $\pi = [\pi_i]$ as steady state probability of X with π_i as the ith element, i.e., $\pi_i = \Pr.\{X = i\}$. Then we can find π from the following relationship:

$$\begin{cases} \pi Q = \pi, \\ \sum_{i=1}^{B} \pi_i = 1. \end{cases} \tag{3.5}$$

Based on the distribution of X, we find the mean of Z. Given $X = x$ at the end of the previous CS interval, the buffer size at the beginning of current CS interval is $Z = x + m$. Furthermore, given that y packets can be transmitted in the current CS interval, then the buffer size changes from $Z = x+m$ to $Z = x+m-1, \ldots, x+m-(y-1)$ during the first y slots, and the buffer size becomes $Z = x+m-y$ in the remaining $(K_{\max} - y)$ slots. Thus, the conditional average buffer size for given x and y is

$$\overline{Z}|_{x,y} = \frac{\sum_{j=0}^{y-1}(x+m-j) + (x+m-y)(K_{\max}-y)}{K}, \tag{3.6}$$

where the first term in the numerator on the right-hand side of (3.6) is for the period when the buffer occupancy keeps decreasing, and the second term is for the period when the buffer occupancy is constant.

The number of packets that can be served in each CS interval is a random variable, which is denoted as Y. The conditional probability of $Y = y$ given $X = x$ is related to the transition probability of X and given by

$$\Pr.\{Y = y|X = x\} = \begin{cases} Q_{x,x+m-y}, & \text{if } x + m \leq B \\ Q_{x,B-y}, & \text{if } x + m > B \end{cases} \tag{3.7}$$

for $y = 0, 1, \ldots, \min\{K, x + m\}$ and $\Pr.\{Y = y|X = x\} = 0$ for other values of y.

Then, the unconditional average buffer size $\overline{Z}$ can be written as

$$\overline{Z} = \sum_{x=0}^{B} \sum_{y=0}^{K} \overline{Z}|_{x,y} \Pr.\{X = x\} \Pr.\{Y = y|X = x\} \tag{3.8}$$

According to the Little's Law, the average packet transmission delay for CBR traffic is given by

$$\overline{D} = \frac{\overline{Z}}{m/T_{CS}} = \frac{\overline{Z}T_{CS}}{m}, \tag{3.9}$$

where m/T_{CS} gives the mean packet arrival rate.

3.2 Delay Analysis for Bursty Traffic

In a practical system, each sensor may have a certain probability to generate data packets to the CH at the beginning of each CS interval, and M, a random variable, is used to represent the total number of packets generated by all the sensors in a CS interval. Let P_b be the probability that each sensor generates a packet in a CS interval and N_s be the total number of sensors. Then $\Pr.\{M = m\}$ is given by

$$\Pr.\{M = m\} = \frac{N_s!}{m!(N_s - m)!} P_b^m (1 - P_b)^{N_s - m} \tag{3.10}$$

for $m = 0, 1, \ldots, M$, and $\Pr.\{M = m\} = 0$ for $m > M$.

Define Z and X the same as in the previous section. Given $M = m$, we can find the transition probability of X from $X = i$ to $X = j$ as

$$Q_{ij,m} = \begin{cases} \sum_{k=i+m}^{K} p_k, & \text{if } j = 0 \text{ and } i + m \leq K, \\ p_{i+m-j}, & \text{if } i + m - K \leq j \leq i + m \text{ and } i + m > K, \\ 0, & \text{otherwise.} \end{cases} \tag{3.11}$$

The unconditional transition probability for each case then can be found as

$$Q_{ij} = \sum_{m=0}^{\infty} Q_{ij,m} \Pr.\{M = m\}. \tag{3.12}$$

Let Y be the number of packets served in the CS interval. Given $Y = y$, the buffer size keeps decreasing from $x + m$ to $x + m - (y - 1)$ in the first y time slots and then becomes $x + m - y$ and is unchanged for the remaining $(K_{\text{max}} - y)$ time slots. Therefore, given x and y, the conditional mean queue size for the entire CS interval is given by

$$\overline{Z}_{m,x,y} = \frac{\sum_{j=0}^{y-1}(x + m - j) + (x + m - y)(K_{\text{max}} - y)}{K_{\text{max}}}. \tag{3.13}$$

The distribution of Y for given X and M is given by

$$\Pr.\{Y = y | X = x, M = m\} = \begin{cases} Q_{x,\ x+m-y,\ m}, & 0 \leq y \leq \min\{K, x + m\}, \\ 0, & \text{otherwise.} \end{cases} \tag{3.14}$$

The mean buffer occupancy can be found as

$$\overline{Z} = \sum_{m=1}^{\infty} \sum_{x,y=0}^{\infty} \overline{Z}_{m,x,y} \Pr.\{X = x\} \Pr.\{Y = y | X = x, M = m\} \Pr.\{M = m\}. \tag{3.15}$$

Using the Little's Formula, the mean delay can be found as

$$\overline{D} = \frac{\overline{Z}}{\overline{M}/T_{CS}}. \tag{3.16}$$

3.3 Delay Analysis for Poisson Traffic

Packet transmission delay for the real-time traffic in the considered network 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) channel time is not reserved for the real-time traffic. One way is to treat the system as an M/G/1 queue with server vacation, and the vacation time is a sum of the time due to reasons ii) and iii). However, analyzing the average delay in such a system is difficult due to the server vacation. Another way is to treat the "vacation" time due to reasons ii) and iii) as part of the *packet service time* (PST). In this case the service system is a standard M/G/1 queue, and the mean delay can be found provided the distribution of the PST is found. Let $\overline{M}$ be the average number of packets generated by all sensors during one CS interval, and τ be the PST. The mean packet transmission delay can be found using the delay formula of the M/G/1 queue as

$$\overline{D} = \mathrm{E}[\tau] + \frac{(\overline{M}/T_{CS})\mathrm{E}[\tau^2]}{2[1-(\overline{M}/T_{CS})/\mathrm{E}[\tau]]} = \mathrm{E}[\tau] + \frac{\overline{M}\mathrm{E}[\tau^2]}{2[T_{CS}-\overline{M}/\mathrm{E}[\tau]]}. \tag{3.17}$$

In the remaining part of this subsection, we find the distribution of τ. We use τ_i to represent the ith PST. As shown in Fig. 3.1, the first PST, or τ_1, starts at time 0. The ith PST starts at the end of the $(i-1)$th PST and lasts until the current packet finishing transmission. In the first CS interval, if $kT_d \leq T_a < (k+1)T_d$, where

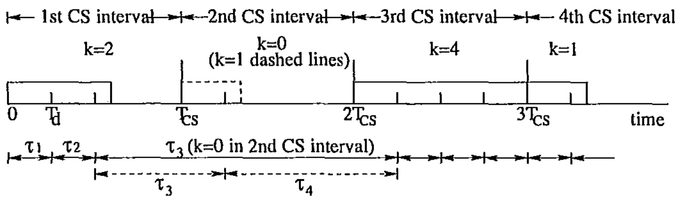

Figure 3.1: Illustration of packet service time

$1 \leq k < K$, then there are k PSTs each with duration of $\tau = T_d$. For the example shown in Fig. 3.1, $k = 2$ and $\tau_1 = \tau_2 = T_d$. The next PST is different as the remaining T_a time in the first CS interval is insufficient to serve one packet. If $T_a \geq T_d$ in the second CS interval as shown in the dashed line, then $\tau_3 = T_{CS} - kT_d + T_d$, where $T_{CS} - kT_d$ is from the first CS interval and T_d is from the second interval. If $T_a < T_d$ from the second CS interval to the $(n+1)$th CS interval (i.e., for n consecutive CS intervals) and $T_a > T_d$ in the $(n+2)$th CS interval, then τ_3 includes the remaining time in the first CS interval after defining τ_1 and τ_2, the next n CS intervals, and the first time slot in the $(n+2)$th CS interval, i.e., $\tau_3 = T_{CS} - kT_d + nT_{CS} + T_d$. In the example shown in Fig. 3.1, when $k = 0$ in the second CS interval, $\tau_3 = T_{CS} - 2T_d + T_{CS} + T_d = 2T_{CS} - T_d$.

We use α_0 to denote the number of PSTs with duration of T_d in a CS interval. When $kT_d \leq T_a < (k+1)T_d$ in a given CS interval, there can be k PSTs each lasting for T_d in the CS interval if $k = K$ in the previous CS interval, or $k - 1$ PSTs each lasting for T_d in the CS interval if $k < K$ in the previous CS interval as the first time slot in the current CS interval is combined with the remaining time in the previous CS interval (and may be earlier CS intervals as well) to form a PST. As a special case, $\alpha = k$ in the first CS interval. Based on these observations, we can find the mean number of PSTs with duration of T_d in a CS interval as

$$\alpha_0 = \sum_{k=1}^{K} \left[(k-1)p_k + p_k p_K\right]. \tag{3.18}$$

Overall, each CS interval with $kT_d \leq T_a < (k+1)T_d$ $(0 \leq k \leq K-1)$ can form k PSTs, and each CS interval with $T_a = KT_d$ forms K PSTs. The mean number of PSTs in a CS interval is then given by $\alpha = \sum_{k=1}^{K} kp_k$. The fraction $\frac{\alpha_0}{\alpha}$ gives the probability of $\tau = T_d$. That is,

$$\text{Pr.}\{\tau = T_d\} = \frac{\alpha_0}{\alpha} = \frac{\sum_{k=1}^{K}\left[(k-1)p_k + p_k p_K\right]}{\sum_{k=1}^{K} kp_k}. \tag{3.19}$$

Among all the PSTs, the probability of having a PST with duration of $T_{CS} - kT_d + nT_{CS} + T_d = (n+1)T_{CS} - (k+1)T_d$ is given by

$$\text{Pr.}\{\tau = (n+1)T_{CS} - (k+1)T_d\} = p_k(p_0)^n(1-p_0), \tag{3.20}$$

where $1 \leq k \leq K$ and $n \geq 0$, but $n = 0$ and $k = K$ cannot be true at the same time since in this case $\tau = T_d$ and it has been considered in (3.18).

Chapter 4

Numerical Results

A generic cluster with one CH and N_s sensors is considered in this work. The system setting is the same as described in Chapter 2. There are N homogeneous channels all with the same statistics of being available and unavailable to the CRSN. The durations of the available and unavailable periods are exponentially distributed. For the CBR traffic, a constant number (m) of packets arrive at the beginning of each CS interval. For the bursty traffic, sensors generate packets with probability P_b at the beginning of each CS interval. For the Poisson traffic, packets arrivals follow poisson distribution and the average inter-arrival time between two consecutive packets generated by a given sensor is T_p. Default parameters are listed in Table 4.1, where the values of P_b and T_p are selected so that on average every sensor generates the same number of packets in each CS interval in the bursty arrival case and in the Poisson arrival case. In the remaining part of the Chapter, Sections 4.1-4.3 show the average packet transmission delay for the real time traffic, Section 4.4 shows the available service time for the BE traffic, Section 4.5 shows the system capacity, and Section 4.6 summarizes the results.

Table 4.1: Default Simulation Parameters

Parameter	Value
Total number of channels N	10
Total number of sensors N_s	20
Arrival rate for CBR traffic m	3
Average available duration $\overline{T}_{on}$	100ms
Average unavailable duration $\overline{T}_{off}$	100ms
Duration of a CS Interval T_{CS}	50ms+T_{sw}
Time for channel switching T_{sw}	2ms
Packet transmission time T_d	5ms
Reserved time interval for real-time traffic T_r	40ms
Packet generating probability for bursty traffic P_b	0.2
Packet inter-arrival time for Poisson traffic T_p	500ms

4.1 Delay Performance for CBR Traffic

Fig. 4.1 shows the average packet transmission delay vs. the total number of channels (N). The figure shows very good match between the simulation and the analytical results. As shown in the figure, the average packet transmissions delay decreases with N. This is due to a lower outage probability when N is larger, which is equivalent to more available channel time over a long term. When N is relatively small, increasing its value can reduce the average delay very significantly, especially when the traffic load is relatively high. On the other hand, when the system capacity is sufficiently large, further increasing its value has only very slight effect on the transmission delay, since the delay is mainly dominated by the queueing delay caused by bursty arrivals of the packets.

Fig. 4.2 shows that the average packet transmission delay decreases with $\overline{T}_{on}$. When $\overline{T}_{on}$ is relatively small, for example, below 400ms in the simulated case, the average packet transmission delay drops very quickly with $\overline{T}_{on}$. As $\overline{T}_{on}$ increases, it has less effect on the average packet transmission delay. This is because when $\overline{T}_{on}$ is much larger than T_{CS}, the probability that an available channel becomes unavailable

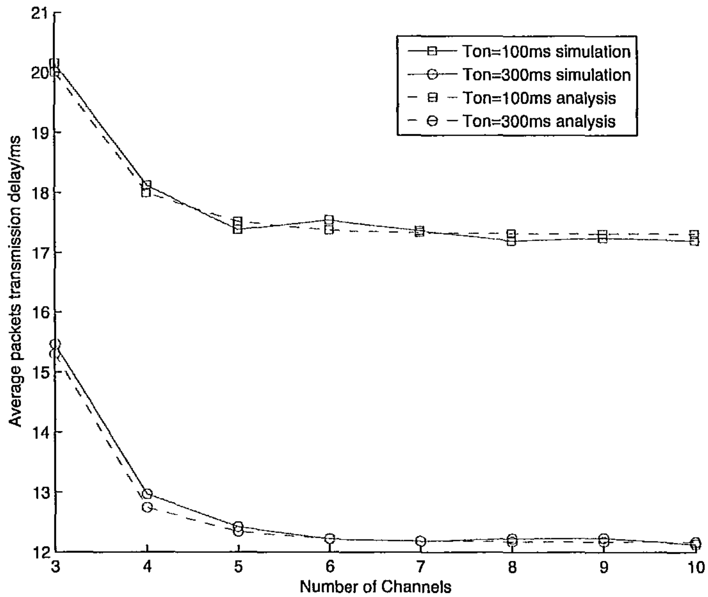

Figure 4.1: Average packet transmission delay vs. number of channels, CBR traffic

before the end of the CS interval is very small. Further increasing $\overline{T}_{on}$ has little effect on the available channel time, and therefore does not affect the system capacity very much.

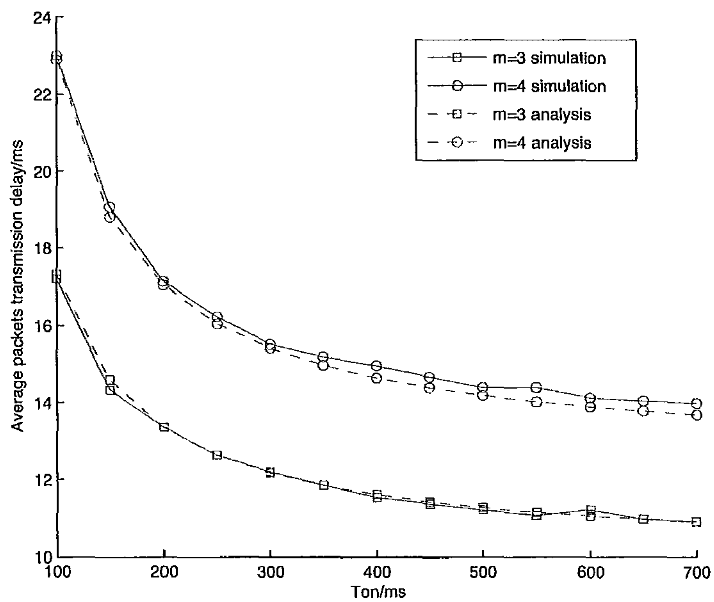

Figure 4.2: Average packet transmission delay vs. $\overline{T}_{on}$, CBR traffic

Fig. 4.3 shows that the average packet transmission delay increases with the total number of packets that arrive in each CS interval. At the point where the increase of average delay becomes very abruptly, we can find the CBR traffic capacity in number of packets per CS interval, which is 7 when $\overline{T}_{on} = 100ms$ and 9 when $\overline{T}_{on} = 300ms$. When m is larger than these values, the service system is unstable.

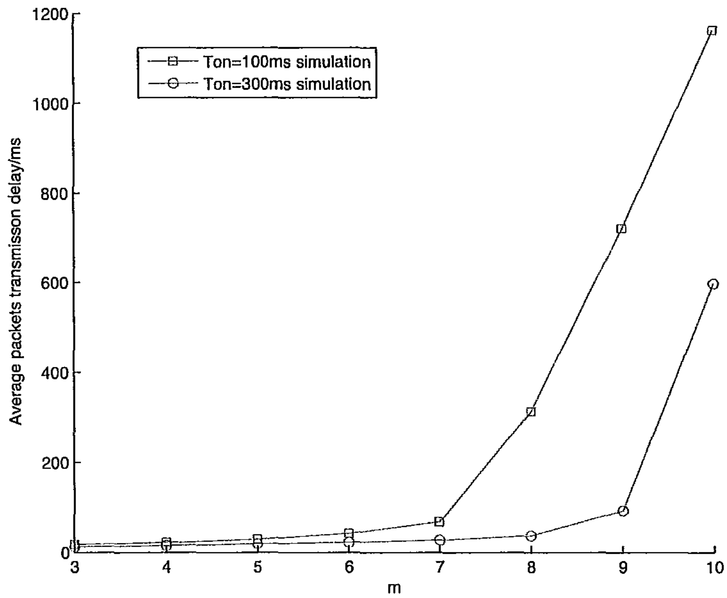

Figure 4.3: Average packet transmission delay vs. m, CBR traffic

4.2 Delay Performance for Bursty Traffic

Fig. 4.4 shows the delay performance of the bursty traffic as $\overline{T}_{on}$ increases. The general trend is the same as the average delay performance for the CBR traffic. The probability that each sensor generates a packet at the beginning of each CS interval is $P_b = 0.2$. When $N_s = 20$ and 25, the average number of packets generated by all the sensors at the beginning of each CS interval is 4 and 5, respectively. Comparing the delay when $N_s = 20$ for the bursty traffic case to the delay when $m = 4$ for the CBR traffic case, we find that the former is much larger. That is, the random arrivals further increase the packet transmission delay.

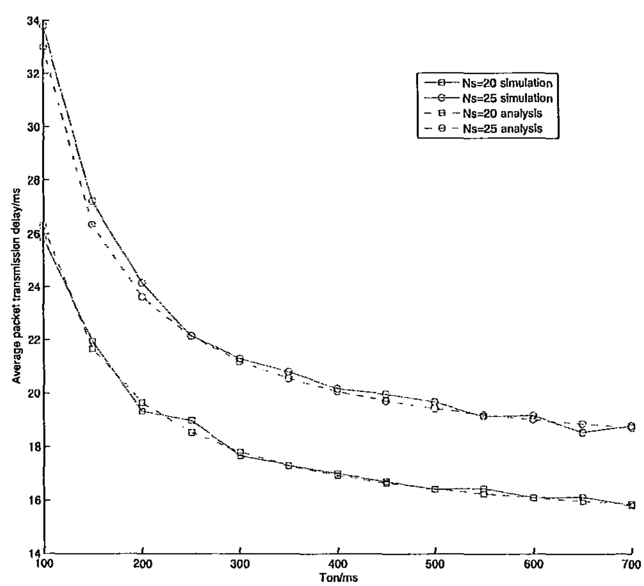

Figure 4.4: Average packet transmission delay vs. $\overline{T}_{on}$, bursty traffic

Fig. 4.5 shows the average packet transmission delay as the number of channels increases. The figure shows the same trend as in the CBR traffic case but much longer delay due to the random packet arrivals.

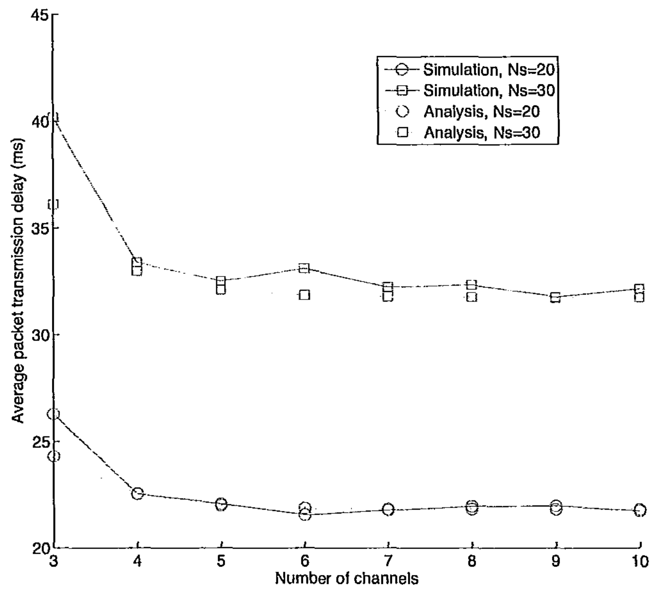

Figure 4.5: Average packet transmission delay vs. number of channels, bursty traffic

Fig. 4.6 shows the average packet transmission delay as the number of sensors increases. We can find the maximum number of sensors that can be supported (before the delay goes to infinity) is 35 when $\overline{T}_{on} = 100$ and 45 when $\overline{T}_{on} = 300$. With $P_b = 0.2$, the numbers are equivalent to 7 and 9 packets that arrive at the beginning of each CS interval on average. These capacity numbers are the same as in the CBR traffic case.

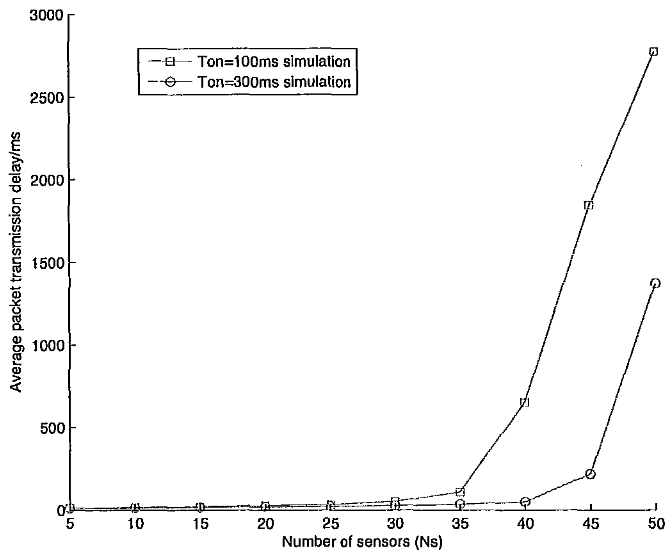

Figure 4.6: Average packet transmission delay vs. number of sensors, bursty traffic

4.3 Comparison of Delay Performance for Bursty and Poisson Traffic

Qualitatively, the relationship between the average packet transmission delay and the network parameters is the same for the Poisson traffic as that for the bursty and CBR traffic. Therefore, in this section we emphasize more comparison between the delay performance of the bursty traffic and the Poisson traffic.

Both Figs. 4.7 and 4.8 demonstrate that the bursty traffic in general experiences shorter average delay than the Poisson traffic. This is because that the sensors have a better chance to transmit in the earlier portion of the CS intervals. Therefore, packets that arrive in later time of a CS interval for the Poisson arrival case can easily miss the transmission chance in the current CS interval and have to be buffered until the

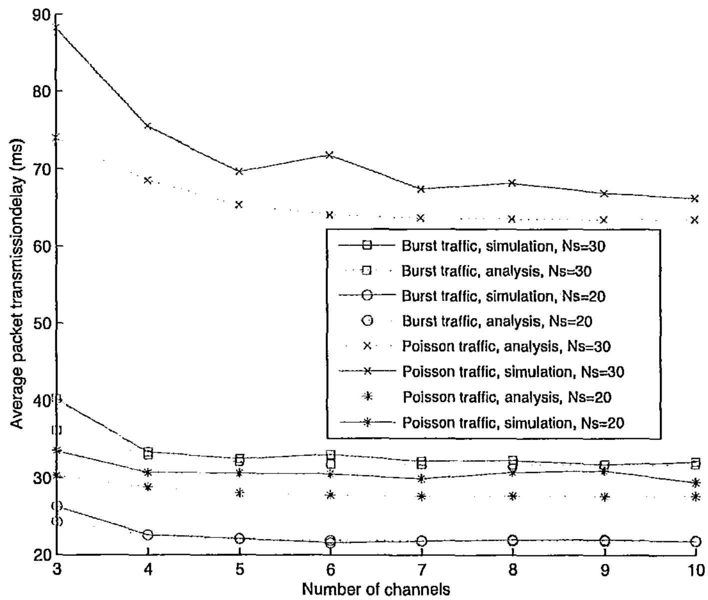

Figure 4.7: Comparison between bursty and Poisson traffic, delay vs. number of channels

next CS interval. On the other hand, for the bursty arrivals, all packets arrive at the beginning of the CS intervals and are more likely to be served in the same CS interval when they arrive.

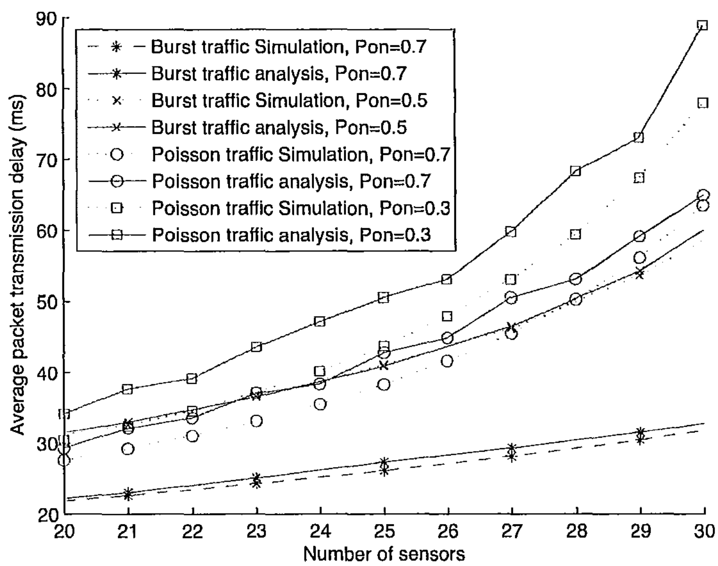

Figure 4.8: Comparison between bursty and Poisson traffic, delay vs. number of sensors

4.4 Available Service Time for BE Traffic

The available service time for the BE traffic depends on how much time is reserved for the real-time traffic. Both Figs.4.9 and 4.10 show more available service time for the BE traffic when the reserved period for the real-time traffic is shorter. Having a larger P_{on} or $\overline{T}_{on}$ can increase the amount of available service time for the BE traffic, but the increase becomes less obvious as P_{on} or $\overline{T}_{on}$ is larger. The reason is similar to the effect of these parameters on the capacity of the real-time traffic.

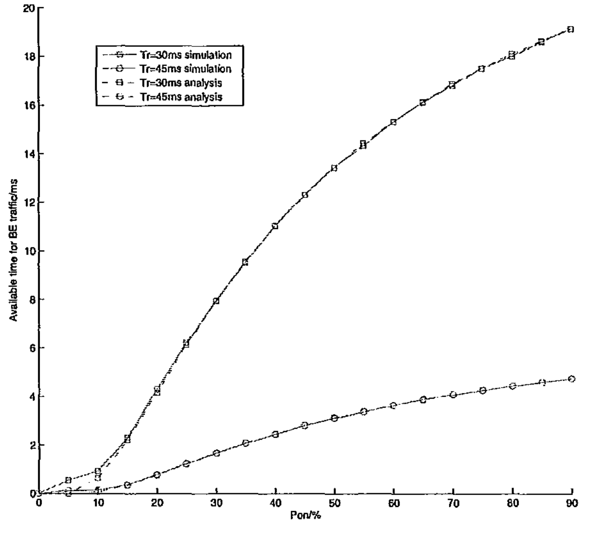

Figure 4.9: Available service time for BE traffic vs. P_{on}

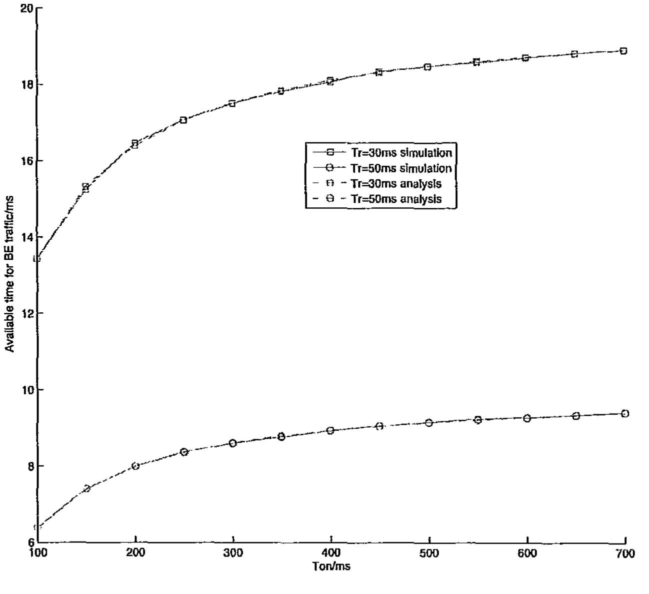

Figure 4.10: Available service time for BE traffic vs. $\overline{T}_{on}$

4.5 System Capacity

The capacity is defined as the maximum number of sensors that system can support. Fig. 4.11 shows the system capacity. Since the capacity is derived without considering the packet transmission delay, it is more precisely the capacity upper bound when considering the real-time traffic. Theoretically, the capacity increases with P_{on} and the number of channels. On the other hand, when these values are sufficiently large, further increasing them does not affect the capacity very much. This is due to that the capacity has reached the limit, which is determined by the number of slots per CS interval and the average number of packets generated by each sensor during each CS interval.

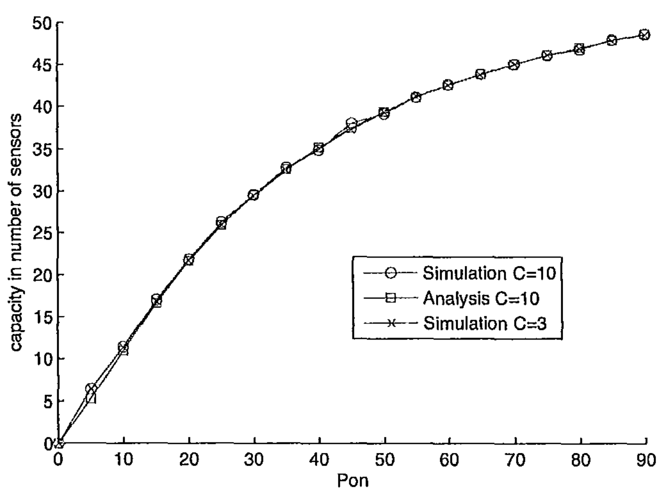

Figure 4.11: System capacity

4.6 Summary

From the numerical results we can find that

- the simulation results match the analytical results very well,
- very low average packet transmission delay (e.g., < 100ms) can be achieved for different types of real-time traffic, and
- the bursty traffic with packets arriving at the beginning of the CS intervals experiences shorter packet transmission delay than the Poisson traffic.

Chapter 5

Conclusion and Future Work

In this thesis, we have introduced a cognitive radio sensor network, where devices can opportunistically access unused channels in the licensed spectrum and both real-time traffic and best effort data traffic can be supported. Resource allocations in the system takes advantage of the channel availability information by serving the real-time traffic in the time interval when the devices have better transmission opportunities. The MAC protocol of the network is based on the IEEE 802.15.4 protocol. The real-time traffic is supported using the contention free transmissions and the non-real-time traffic is served using the contention-based transmissions.

We have derived the average packet transmission delay for different types of real-time traffic. For both the CBR and the bursty traffic, an embedded Markov chain is formulated, based on which the average packet transmission delay is found. For the Poisson traffic, an M/G/1 queue is formulated, where the packet service time is defined in order to take into consideration the time intervals during which the real-time traffic cannot be transmitted due to different reasons.

Computer simulation results have verified the accuracy of the analysis. Furthermore, the results show good potential of supporting real-time traffic in the CRSN. That is, very low average transmission delay can be supported in the CRSN. In addition, the results indicate that packets with the Poisson arrivals can experience longer average delay than packets with the bursty arrivals.

For practical applications, real-time packets can be dropped if their experienced transmission delay exceeds a certain threshold. Next we will study how to allocate the radio resources in order to balance the requirements of low packet drop rate and high resource utilization in the CRSN. We will also analyze the system capacity by taking into consideration the delay requirements of the real-time traffic. Performance of multi-cluster CRSNs with mixed real-time and best effort traffic will also be studied.

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