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

Zhongliang Liang, Shan Feng, Dongmei Zhao, and Xuemin (Sherman) Shen

***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 paper we introduce a cognitive radio sensor network (CRSN) and analyze its performance for supporting real-time traffic. The network opportunistically accesses vacant channels in the licensed spectrum. When the current channel becomes unavailable, the devices can switch to another available channel. Two types of channel switchings are considered, in periodic switching (PS) the devices can switch to a new channel only at the beginning of each channel switching (CS) interval, while in triggered switching (TS) the devices can switch to a new channel as soon as the current channel is lost. We consider two types of real-time traffic, i) 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. We derive the average packet transmission delay for each type of the traffic and channel switching mechanisms. Our results indicate that real-time traffic can be effectively supported in the CRSN with small average packet transmission delay. For the network using PS, packets with the Poisson arrivals experience longer average delay than the bursty arrivals; while for the network using TS, packets with the bursty arrivals experience longer average delay.**

***Index Terms*—Wireless sensor networks, cognitive radio networks, real-time traffic, performance analysis.**

I. INTRODUCTION

UBIQUITOUS wireless sensor networks (WSNs) are expected to play an important role in the future society. Providing data transmissions with guaranteed quality of service (QoS) is of great importance in various areas such as health care and environmental monitoring. 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 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 real-time services is becoming a key issue in future WSNs. Currently, most WSNs work in the license-free band and are expected to suffer from heavy interference caused by other networks sharing the same spectrum [1]-[2]. Providing QoS in such networks can be very difficult as the license-free spectrum becomes increasingly crowded. For example, the sensor nodes may have to identify the type of interferer and switch to different channels from time to time [3]. The coexistence of multiple networks in the same license-free spectrum also brings challenging issues 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.

Building a cognitive radio network (CRN) 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 resources that can possibly be used to transmit traffic with high bandwidth and low latency requirements [4]. On the other hand, there are a lot of challenging and open issues to build a practical CRN, including effective and efficient spectrum sensing and spectrum allocations, minimum potential interference to the primary network, etc. A good survey regarding problems and possible solutions for CRNs can be found in [5]. 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 [6] and [7], 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 [8]. Other works studying real-time performance for traffic in CRNs can be found in [9]-[12]. There have been some efforts recently on combining WSNs and cognitive radio technology, and some general implementation issues are discussed in [13] and [14]. Possible implementations of a cognitive radio sensor network (CRSN) is presented in [15] from a system level point of view. Energy efficiency in a CRSN with multi-carrier modulation is studied in [16] and [17]. In [18] performance of a CRSN for supporting health care traffic is studied. In [19] and [20], two methods are considered for prioritizing the real-time traffic over the best effort (BE) traffic in the CRSN, a reservation-based method and an absolute priority method, and analytical models are derived to find the delay performance for supporting constant-bit-rate (CBR) traffic and the amount of channel time available for the BE traffic. In the reservation-based method, each type of the traffic can only be served when

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Z. Liang, S. Feng, and D. Zhao are with the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada (e-mail:{zliang, fengs2, dzhao}@mcmaster.ca).

X. Shen is with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada (e-mail: xshen@bbcr.uwaterloo.ca).

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a channel is available during the pre-allocated time intervals; while in the absolute priority method, the real-time traffic can be served whenever a channel is available, and the BE traffic can only be served when there is no buffered real-time traffic.

In this work we extend the reservation-based method in [19] and [20] and study the performance for supporting random real-time traffic in a CRSN. The network opportunistically accesses available channels in the licensed spectrum. When the current channel becomes unavailable, the devices can switch to a different channel. Two types of channel switchings are considered, in periodic switching (PS) the devices can switch to a new channel only at the beginning of each channel switching (CS) interval, while in triggered switching (TS) the devices can switch to a new channel as soon as the current channel is lost. We consider two types of real-time traffic, i) 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 and channel switching mechanisms, we derive the average packet transmission delay. The remainder of the paper is organized as follows. In Section II we describe the CRSN, including the CS mechanisms and radio resource allocations. The distribution of available channel time during each CS interval is derived in Section III. Based on these results, average packet transmission delay is derived in Section IV for the bursty traffic and in Section V for the Poisson traffic. Numerical results are demonstrated in Section VI, and Section VII concludes the paper.

II. Overview of a CRSN

We consider a number of sensors that communicate directly with a central station, which can be a cluster head (CH) in a multi-cluster network. 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 WSN, data transmissions are mainly from the sensors to the CH, and transmissions from the CH to the sensors are mainly for sending acknowledgment (ACK) frames, channel allocation messages, and other control signaling messages. In multi-hop transmissions, the real-time data collected by the CH from the sensors are forwarded to the next hop CH and further to the sink. Due to the strict timeline arrangement of the CHs (as will be detailed later in this section), timeline coordinations between the CHs can be another complicated issue, and can introduce considerable delay in multihop transmissions [21] [22]. In order to keep short transmission delay, the real-time traffic collected by the CH can be either processed locally, if the CH is co-located with the data sink, or forwarded to a data sink through a high-speed wireless communication network, such as an IEEE 802.16-based wireless metropolitan area network, or a wireline communication network. In either of the 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 the transmission delay between the sensors and the CH within a cluster.

The CRSN opportunistically accesses vacant channels in a spectrum. Each cluster requires only one available frequency channel at any time due to that the CH has only one radio for data communications. The sensor nodes have to switch between different channels depending on channel availability. It is possible that the sensors operate on multiple channels, and more information about real sensor nodes with multi-channel function can be found in [23] and [24]. 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 be large, especially when there are 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, one is dedicated for channel sensing, and the other is for data communications. Multi-radio WSNs have been studied in the literature and some examples can be found in [25]-[27]. With a 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 a fixed value T_{sw} to represent the time for the devices to switch to a new channel, if there is a channel available after the previous one is lost. 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 [30]. Therefore, in the one-radio case, T_{sw} can also be approximated as a fixed value.

A dedicated control channel is used for the CH to notify the sensors about the current available channels. Designing a CRSN without a dedicated control channel can be found in [28]. 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 can be avoided in different ways. First, a different set of candidate channels can be assigned to neighboring clusters if the number of candidate channels is sufficiently large. 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 [21] and [29].

A. Channel switching

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 may simply wait 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. This is referred to as periodic switching (PS). On the other hand, the CH may notify the sensors a new channel (if there is one available) as soon as the previous channel is lost, and this is referred to as triggered (by a channel loss) switching (TS). The total number of channel switchings in each CS interval is either zero or one for PS, depending on whether there is a channel available at the beginning of the CS interval. For TS, the number of channel switchings is a random variable. Using TS allows the CRSN to have more channel time than using PS. On the other hand, sensors in a network using PS can simply go to a power saving mode after detecting a channel loss and do not have to be active until the beginning of the next CS interval. Therefore, synchronization between the sensors and the CH is much easier using PS. More comparison between networks using the two CS mechanisms will be given in Section VI.

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. For PS, the CH and the sensors switch to the power saving mode if no channel is available at the beginning of a CS interval. For TS, the sensors switch to the control channel as soon as they realize a channel loss, and keep listening to the control channel until a vacant channel is available.

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 unnecessary interference to the primary network.

B. Traffic and resource allocation

Both real-time traffic and best effort (BE) data traffic can be served, but the real-time traffic is given a higher priority and its performance is not affected by 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). During the GTS period, an amount of T_r radio time is reserved for the real-time traffic, and the remaining radio time can be used for the BE traffic. The actual amount of *available channel time*, denoted as T_a, for serving the real-time traffic in the reserved time interval is random due to the random channel availability.

For PS, after an available channel is lost, no channel is available for the rest of the 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 followed by GTSs. In order to have the CRSN fit into the IEEE 802.15.4 MAC, we can carefully arrange the timelines of the MAC superframes and the CS intervals 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. 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 [20] when $T_{CS} \neq T_{SF}$. For TS, the timeline arrangement between the CS intervals and the superframes is not as critical as for PS since a new channel may be available at anytime during a CS interval, but we adopt the same arrangement as for PS to simplify the presentation.

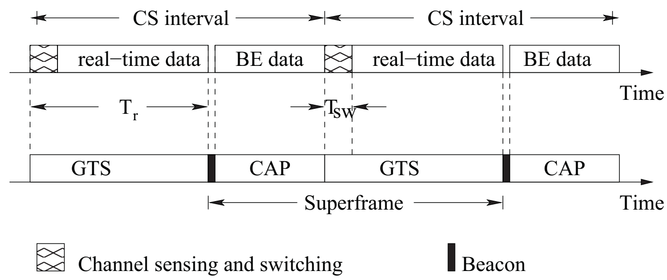

Fig. 1. Superframe vs. CS interval.

III. DISTRIBUTION OF AVAILABLE CHANNEL TIME

We consider that the CRSN opportunistically accesses a number of C frequency channels. All the channels have the same statistical activities. That is, they all have the same distribution for their channel available intervals (CAIs) and the same distribution for their channel unavailable intervals (CUIs). Each CAI (or CUI) is a time interval during which a given channel is continuously available (or unavailable) to the CRSN. The availability of different channels is assumed to be independent of each other. Let random variables T_{on} and T_{off}, respectively, represent the duration of a CAI and a 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 $\overline{T}_{out} = \frac{\overline{T}_{off}}{C}$.

In the remaining part of this section we derive the distribution of T_a, which is the amount of available channel time in the time interval reserved for the real-time traffic. This distribution is important for analyzing delay performance of the service system.

A. Distribution of T_a when using PS

When all the channels are unavailable, $T_a = 0$. That is, Pr.$\{T_a = 0\} = P_{out}$. If there is at least one channel available

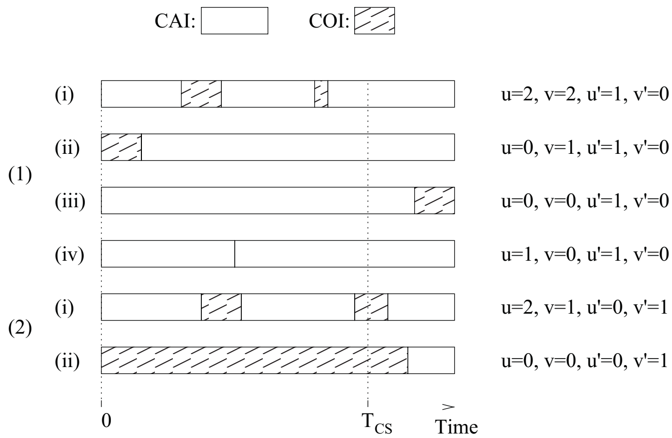

Fig. 2. Timelines of CAIs and COIs vs. CS interval.

and $T_{on} < T_r$, then $T_a = T_{on}$. Therefore, for any $0 < t_a < T_r$, we have

$$\begin{aligned} \Pr.\{T_a \le t_a\} &= P_{out} + (1 - P_{out})\Pr.\{T_{on} \le t_a\} \\ &= P_{out} + (1 - P_{out})\left(1 - e^{-\frac{t_a}{\overline{T}_{on}}}\right). \quad (1) \end{aligned}$$

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

$$\begin{aligned} \Pr.\{T_a = T_r\} &= (1 - P_{out})\Pr.\{T_{on} \ge T_r\} \\ &= (1 - P_{out})e^{-\frac{T_r}{\overline{T}_{on}}}. \quad (2) \end{aligned}$$

The probability density function (pdf) of T_a is given by

$$\begin{aligned} f(t_a) &= P_{out}\ \delta(t_a) + \frac{1 - P_{out}}{\overline{T}_{on}}\ e^{-\frac{t_a}{\overline{T}_{on}}} \\ &\quad +(1 - P_{out})\ e^{-\frac{T_r}{\overline{T}_{on}}}\ \delta(t_a - T_r) \quad (3) \end{aligned}$$

for $0 \le t_a \le T_r$, where $\delta(\cdot)$ is the Dirac delta function. Note that the second term on the right-hand side of (3) is the derivative of the right-hand side of (1) with respect to t_a.

B. Distribution of T_a when using TS

When using TS, the reserved interval may consist of multiple CAIs and COIs. As shown in Fig. 2, the reserved interval may end in the middle of a CAI or COI and this CAI or COI 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 the latter to 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 ($U \ge 0$) and V ($V \ge 0$), 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. Define S as the total number of channel switchings in the reserved time interval, $S = U + U'$. Although U can be any integer from zero to infinity, there can be at most $S_{\max} = \lceil T_r/T_{sw} \rceil$ successful channel switchings performed within the reserved time interval. Since the probability of $T_{on} < T_{sw}$ is very small, we assume that all NCAIs last for at least T_{sw}, and the maximum value of U is $S_{\max}$ if $U' = 0$ and $S_{\max} - 1$ if $U' = 1$. For U and V, we have $V \le U+1$. 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

$$B(u + 1, v, P_{out}) = \binom{u+1}{v} P_{out}^{v}(1 - P_{out})^{u+1-v}. \quad (4)$$

The duration of each NCAI follows an exponential distribution with mean $\overline{T}_{on}$. When $U = u \ge 1$, the total amount of the NCAI time in the reserved time interval follows an Erlang-u distribution with a pdf given by

$$p_{e,on}(t, u) = \frac{t^{u-1}e^{-\frac{t}{\overline{T}_{on}}}}{\overline{T}_{on}^{u}(u - 1)!}. \quad (5)$$

Similarly, when $V = v \ge 1$, the total amount of the NCOI time in the reserved time interval follows an Erlang-v distribution with a pdf given by

$$p_{e,out}(t, v) = \frac{C^{v}t^{v-1}e^{-\frac{Ct}{\overline{T}_{off}}}}{\overline{T}_{off}^{v}(v - 1)!}. \quad (6)$$

Notations $p_{e,on}(t, u)$ and $p_{e,out}(t, v)$ defined in (5) and (6), respectively, will be used later in this section in order to make concise expressions when deriving the pdf of T_a.

The total available channel time in the reserved time interval is a sum of U NCAIs and a TCAI if $U' = 1$, and the amount of total unavailable channel time in the reserved time interval is a sum of V NCOIs and a TCOI if $V' = 1$. 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. 2 based on values of U and V. Below we treat each (sub)case separately.

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

In this case, there is no TCOI in the reserved time interval, and $T_r - T_a$ 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 $0 \le t < T_a$ and $T_a - t$ gives the amount of TCAI time. As the duration of the reserved time interval is fixed at T_r, the variables T_a, U, and V are dependent on each other and their joint pdf is given by

$$\begin{aligned} f_1(t_a, u, v) &= \int_0^{t_a-} p_{e,on}(t, u)\ p_{e,out}(T_r - t_a, v) \\ &\quad \times\ B(u + 1, v, P_{out})\ \Pr.\{T_{on} > t_a - t\}dt, (7) \end{aligned}$$

where $p_{e,on}(t,u)$ and $p_{e,out}(T_r - t_a, v)$, respectively, give the pdf of having u NCAIs with total duration of t and v NCOIs with total duration of $T_r - t_a$, Pr.$\{T_{on} > t_a - t\}$ gives the probability of existing 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

$$f_1(t_a, 0, v) = P_{out}\ p_{e,out}(T_r - t_a, 1)\ \text{Pr.}\{T_{on} \geq t_a\}, \quad (8)$$

where $p_{e,out}(T_r - t_a, 1)$ gives the pdf of the NCOI with duration $T_r - t_a$, 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, $T_a = T_r$. This happens when there is at least one channel available at the beginning of the CS interval and the channel is available for the entire reserved time interval. Then we have

$$\text{Pr.}\{T_a = T_r, U = 0, V = 0\} = (1 - P_{out})\text{Pr.}\{T_{on} \geq T_r\}, \quad (9)$$

where the first equality is due to that when $T_a = T_r$ and $U = 0$, V can only be zero.

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

$$\begin{aligned}\text{Pr.}\{T_a = T_r, U = u, V = 0\} &= \text{Pr.}\{T_a = T_r, U = u\} \\ = (1 - P_{out})^{u+1} &\int_0^{T_r -} p_{e,on}(t,u)\ \text{Pr.}\{T_{on} > T_r - t\} dt \quad (10)\end{aligned}$$

for $u > 0$, 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.$\{T_{on} > T_r - t\}$ gives the probability of existing one TCAI.

By combining all the four subcases we can find the joint pdf of T_a and U and the pdf of T_a in case (1) as

$$\begin{aligned} f_1(t_a, u) &= \sum_{v=1}^{u+1} f_1(t_a, u, v) + \delta(t_a - T_r) \\ &\quad \times \text{Pr.}\{T_a = T_r, U = u\} \quad (11)\end{aligned}$$

and

$$\begin{aligned} f_1(t_a) &= \sum_{u=0}^{S_{\max}-1} \sum_{v=1}^{u+1} f_1(t_a, u, v) + \delta(t_a - T_r) \\ &\quad \times \sum_{u=0}^{\infty} \text{Pr.}\{T_a = T_r, U = u\}. \quad (12)\end{aligned}$$

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

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

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

$$\begin{aligned} f_2(t_a, u, v) = p_{e,on}(t_a, u) B(u, v, P_{out}) &\int_{t=0}^{(T_r - t_a)-} p_{e,out}(t, v) \\ &\text{Pr.}\{T_{out} > T_r - t_a - t\} dt \quad (13)\end{aligned}$$

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.$\{T_{out} > T_r - t_a - t\}$ is the probability of existing one TCOI.

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

$$\begin{aligned} f_2(t_a, u, 0) &= p_{e,on}(t_a, u)\ (1 - P_{out})^u \\ &\int_{t=0}^{(T_r - t_a)-} \text{Pr.}\{T_{out} \geq T_r - t_a - t\} dt. \quad (14)\end{aligned}$$

As a special case, we define $f_2(t_a, 0, 0) = 0$.

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

$$\text{Pr.}\{T_a = 0, U = 0\} = \text{Pr.}\{T_{out} \geq T_r\} = e^{-\frac{CT_r}{T_{off}}}. \quad (15)$$

Combining both the subcases, the joint pdf of T_a and U and the overall pdf of T_a in case (2) are given by

$$f_2(t_a, u) = \sum_{v=0}^{u} f_2(t_a, u, v) + \delta(t_a)\delta(u)\text{Pr.}\{T_a = 0, U = 0\}, \quad (16)$$

$$f_2(t_a) = \sum_{u=1}^{S_{\max}} \sum_{v=0}^{u} f_2(t_a, u, v) + \delta(t_a)\ \text{Pr.}\{T_a = 0\}. \quad (17)$$

Combining (12) and (17) we find the pdf of T_a as $f(t_a) = f_1(t_a) + f_2(t_a)$. Since $S = U + U^{'} = U + 1$ in case (1) and $S = U + U^{'} = U$ in case (2), the joint pdf of T_a and S can be found as $f_{T_a,S}(t_a, s) = f_1(t_a, s-1) + f_2(t_a, s)$.

IV. Delay Performance of Bursty 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 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 CS interval, and M represents the total number of packets sent by all the sensors in a CS interval. 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 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

[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.

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, and the mean of Z can then be obtained.

A. Delay performance when using PS

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 unavailable and channel switching. 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 $k < 0$. For $k \geq 0$, we can find p_k as

$$\begin{aligned} p_k &= \text{Pr.}\{kT_d + T_{sw} \leq T_a < (k+1)T_d + T_{sw}\} \\ &= \int_{kT_d+T_{sw}}^{(k+1)T_d+T_{sw}} f(t_a)dt_a. \end{aligned} \tag{18}$$

Consider a typical CS interval as the reference CS interval. Given $M = m$ in the reference CS interval and $X = x$ in the previous CS interval, there are $x + m$ packets in the virtual buffer at the beginning of the reference CS interval, and the probability of $X = x^{'}$ at the end of the reference CS interval can be found from the following conditional transition probability

$$Q_{xx',m} = \begin{cases} \sum_{k=x+m}^{\infty} p_k, & \text{if } x^{'} = 0, \\ p_{x+m-x'}, & \text{if } x^{'} \leq x+m, \\ 0, & \text{otherwise.} \end{cases} \tag{19}$$

The unconditional transition probability of X then can be found as

$$Q_{xx'} = \sum_{m=0}^{\infty} Q_{xx',m} \text{Pr.}\{M = m\}. \tag{20}$$

The steady-state probability of X, $\text{Pr.}\{X = x\}$, can then be found from (20). Let $Y = y$ be the number of packets served in the reference CS interval. The distribution of Y for given X and M is given by

$$\begin{aligned} &\text{Pr.}\{Y = y | X = x, M = m\} \\ &\quad = \begin{cases} Q_{x,\ x+m-y,\ m}, & \text{if } 0 \leq y \leq x+m, \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \tag{21}$$

The buffer size is constant for the T_{sw} interval at the beginning of the CS interval. It then keeps decreasing by 1 in every T_d interval in the next yT_d interval, and this changes the buffer size from $x + m$ to $x + m - y$. The buffer size then is unchanged for the remaining $(T_{CS} - T_{sw} - yT_d)$ time. Therefore, given m, x and y, the conditional mean of the queue size for the entire CS interval is given by

$$\begin{aligned} \text{E}[Z|m,x,y] = \Big[&(x+m)T_{sw} + \textstyle\sum_{j=0}^{y-1}(x+m-j)T_d \\ &+ (x+m-y)(T_{CS} - T_{sw} - yT_d)\Big] / T_{CS}. \end{aligned} \tag{22}$$

The mean of the buffer occupancy can be found as

$$\begin{aligned} \text{E}[Z] = &\sum_{m=0}^{\infty}\sum_{x=0}^{\infty}\sum_{y=0}^{K} \text{E}[Z|m,x,y] \text{Pr.}\{Y = y | X = x, M = m\} \\ &\times \text{Pr.}\{X = x\}\ \text{Pr.}\{M = m\}. \end{aligned} \tag{23}$$

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

$$\text{E}[D] = \frac{\text{E}[Z]}{\overline{M}/T_{CS}}. \tag{24}$$

B. Delay performance when using TS

When using TS, the number of packets that can be served in the reserved time interval not only depends on T_a, but also S. We define $p_{k,s}$ 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 that $S = s$ in the reserved interval. Then

$$\begin{aligned} p_{k,s} &= \{kT_d + sT_{sw} \leq T_a < (k+1)T_d + sT_{sw} | S = s\} \\ &= \frac{1}{\text{Pr.}\{S = s\}} \int_{kT_d+sT_{sw}}^{(k+1)T_d+sT_{sw}} f_{T_a,S}(t_a, s)dt_a, \end{aligned} \tag{25}$$

where $\text{Pr.}\{S = s\} = \int_0^{T_r} f_{T_a,S}(t_a, s)dt_a$. As a special case, $p_{k,s} = 0$ for $k < 0$. Following the same process as in the previous subsection, we can find the transition probability of X for given $M = m$ and $S = s$ as

$$Q_{xx',m,s} = \begin{cases} \sum_{k=x+m}^{\infty} p_{k,s}, & \text{if } x^{'} = 0, \\ p_{x+m-x',s}, & \text{if } x^{'} \leq x+m, \\ 0, & \text{otherwise.} \end{cases} \tag{26}$$

The unconditional transition probability of X then can be found as

$$Q_{xx'} = \sum_{s=0}^{S_{\max}} \sum_{m=0}^{\infty} Q_{xx',m,s} \text{Pr.}\{M = m\} \text{Pr.}\{S = s\}. \tag{27}$$

The steady state probability of X then can be found from (27). Let $Y = y$ be the number of packets served in the reference CS interval. Similar to (21) we can find

$$\begin{aligned} &\text{Pr.}\{Y = y | X = x, M = m, S = s\} \\ &\quad = \begin{cases} Q_{x,\ x+m-y,\ m,s}, & \text{if } 0 \leq y \leq x+m, \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \tag{28}$$

When using TS, the available channel time is divided into discontinuous and random intervals. Therefore, the change of buffer size depends on not only the duration of each NCAI and TCAI, but also the duration of each NCOI and TCOI. Mathematically, the conditional mean of the buffer occupancy, given the number of channel switchings, duration of each NCAI, NCOI, TCAI and TCOI, can be found using an equation similar to (22). However, $S_{\max}$ can be large, which means that there can be up to the same number of NCAIs and NCOIs in the reserved time interval. This results in very high complexity to remove all the conditions in order to find the mean of the buffer occupancy from the conditional mean. Therefore, we approximate the calculation by rearranging the channel time in the reserved time interval so that all the NCAIs (and TCAI if there is one) in the reserved time interval follow each other one by one in front of all NCOIs (and TCOI if there is one). Furthermore, all the channel switching time is moved to the beginning of the CS interval. Then for given m,

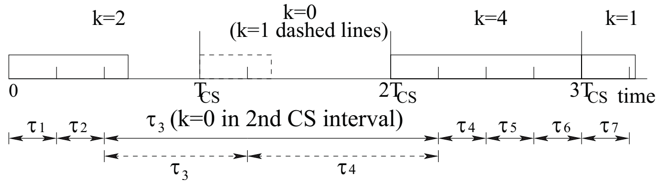

Fig. 3. Packet service time in PS.

x, y and s, the conditional mean of the queue size for the entire CS interval is given approximately by

$$\begin{aligned}\mathrm{E}[Z|m,x,y,s] \;&=\; [(x+m)sT_{sw}+\textstyle\sum_{j=0}^{y-1}(x+m-j)T_d \\ &\quad +(x+m-y)(T_{CS}-sT_{sw}-yT_d)]/T_{CS}, \quad (29)\end{aligned}$$

where the first term in the numerator on the right-hand side of (29) is for all the channel switching time during which the buffer size is unchanged, the second term is for the period during which packets are transmitted, and the third term is for the remaining time of the CS interval. After removing the conditions, the mean of the buffer occupancy can be found as

$$\begin{aligned}\mathrm{E}[Z] = &\sum_{s=0}^{S_{\max}}\sum_{m,x=0}^{\infty}\sum_{y=0}^{K}\mathrm{E}[Z|m,x,y,s]\mathrm{Pr.}\{M=m\}\mathrm{Pr.}\{S=s\} \\ &\mathrm{Pr.}\{Y=y|X=x,M=m,S=s\}\ \mathrm{Pr.}\{X=x\}. \quad (30)\end{aligned}$$

We can then use (24) to find the approximate average packet transmission delay.

V. Delay Performance of Poisson Traffic

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.

A. Delay performance when using PS

The unavailable and non-reserved time due to reasons ii) and iii) can be treated 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. We use λ to represent the mean aggregate packet arrival rate, and τ the PST. The mean of the packet transmission delay is given by

$$\mathrm{E}[D] = \mathrm{E}[\tau] + \frac{\lambda \mathrm{E}[\tau^2]}{2(1-\lambda/\mathrm{E}[\tau])}. \quad (31)$$

As shown in Fig. 3, the channel time after the initial channel switching time in each CS interval is divided into equal length time slots each with duration T_d. The number of time slots in the reserved time interval is $K = \frac{T_r - T_{sw}}{T_d}$, which is assumed to be an integer. The current PST starts at the end of the previous PST and lasts until the end of the first time slot during which a channel is continuously available. We use τ_i to represent the ith PST and define three types of PSTs based on their durations. Each type I PST lasts for $T_{sw}+T_d$, and each Type II PST lasts for T_d. All PSTs that are not Types I and II belong to Type III.

The first PST, or τ_1, starts at the beginning of the first CS interval. If $T_a \geq T_{sw}+T_d$ for the CS interval, $\tau_1 = T_{sw}+T_d$. This is a Type I PST. Furthermore, if $kT_d+T_{sw} \leq T_a < (k+1)T_d+T_{sw}$, where $2 \leq k < K$, then there are $k-1$ Type II PSTs each with duration of $\tau = T_d$. For the example shown in Fig. 3, $k=2$ in the first CS interval, and $\tau_2 = T_d$, which is the only Type II PST in the CS interval. The next PST is different as the remaining T_a time in the first CS interval is insufficient to serve one packet. If $T_a \geq T_d + T_{sw}$ in the second CS interval as shown in the dashed line, then $\tau_3 = (T_{CS}-T_{sw}-2T_d)+(T_d+T_{sw})$, where $T_{CS}-T_{sw}-2T_d$ is from the first CS interval and T_d+T_{sw} is from the second CS interval. After the first CS interval, if $T_a < T_d+T_{sw}$ in the next n ($n=1$ as shown in the dotted line) CS intervals and $T_a > T_{sw}+T_d$ in the following CS interval, we have $\tau_3 = (T_{CS}-T_{sw}-2T_d)+nT_{CS}+(T_{sw}+T_d) = (n+1)T_{CS}-T_d$. This is a Type III PST.

Let α_1 and α_2, respectively, denote the number of Type I and Type II PSTs in a CS interval, and α denote the total number of PSTs in a CS interval. Overall, each CS interval with $kT_d+T_{sw} \leq T_a < (k+1)T_d+T_{sw}$ $(0 \leq k \leq K-1)$ forms k PSTs, and each CS interval with $T_a = KT_d+T_{sw}$ forms K PSTs. The mean number of PSTs in a CS interval is then given by $\overline{\alpha} = \sum_{k=1}^{K} kp_k$. For a given CS interval, $\alpha_1 = 1$ only when $T_a \geq T_{sw}+T_d$ in the CS interval and $T_a = KT_d+T_{sw}$ in the previous CS interval. As a special case, $\alpha_1 = 1$ in the first CS interval. Therefore, the mean of α_1 is $\overline{\alpha}_1 = \sum_{k=1}^{K} p_k p_K$. When $kT_d+T_{sw} \leq T_a < (k+1)T_d+T_{sw}$ for $1 \leq k \leq K-1$, $\alpha_2 = k-1$. When $T_a = KT_d+T_{sw}$, $\alpha_2 = K-1$. Therefore, the mean of α_2 is $\overline{\alpha}_2 = \sum_{k=1}^{K}(k-1)p_k$. The fractions $\frac{\overline{\alpha}_1}{\overline{\alpha}}$ and $\frac{\overline{\alpha}_2}{\overline{\alpha}}$, respectively, give the probability of $\tau = T_d+T_{sw}$ and $\tau = T_d$. That is,

$$\mathrm{Pr.}\{\tau = T_d+T_{sw}\} = \frac{\overline{\alpha}_1}{\overline{\alpha}} = \frac{\sum_{k=1}^{K} p_k p_K}{\sum_{k=1}^{K} kp_k} \quad (32)$$

$$\mathrm{Pr.}\{\tau = T_d\} = \frac{\overline{\alpha}_2}{\overline{\alpha}} = \frac{\sum_{k=1}^{K}(k-1)p_k}{\sum_{k=1}^{K} kp_k}. \quad (33)$$

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

$$\mathrm{Pr.}\{\tau = (n+1)T_{CS}-(k-1)T_d\} = p_k(p_0)^n(1-p_0), \quad (34)$$

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 $\tau = T_d+T_{sw}$ and the PST is in Type I.

B. Delay performance when using TS

For the system using TS, we consider the unavailable channel time during the reserved time interval as part of the 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 times are 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_r, the amount

TABLE I
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
Scheduling Interval T_{CS}	50ms+T_{sw}
Time for channel switching T_{sw}	2ms
Number of sensors N	30
Packet transmission time T_d	5ms
Duration of reserved time interval T_r	50ms
Packet generating probability for bursty traffic P_b	0.2
Packet inter-arrival time for Poisson traffic T_p	260ms

of time available for packet transmissions is $T_a - ST_{sw}$. On average, in every time unit the amount of available channel time for packet transmissions is $(T_a - ST_{sw})/T_r$. In order to serve one packet, the amount of available channel time in each PST of duration τ is T_d. That is, $\tau = \frac{T_d T_r}{T_a - ST_{sw}}$ for $T_a > ST_{sw}$. With this approximation, all the PSTs in the same CS interval are of the same length. However, since T_a is random, τ is also random when considering different CS intervals. Then we can find E$[\tau]$ and E$[\tau^2]$ approximately as

$$\mathrm{E}[\tau] = \sum_{s=1}^{S_{\max}} \int_{sT_{sw}+}^{T_r - sT_{sw}} \frac{T_d T_r}{t_a - sT_{sw}} f_{T_a,S}(t_a, s) dt_a, \quad (35)$$

$$\mathrm{E}[\tau^2] = \sum_{s=1}^{S_{\max}} \int_{sT_{sw}+}^{T_r - sT_{sw}} \left(\frac{T_d T_r}{t_a - sT_{sw}}\right)^2 f_{T_a,S}(t_a, s) dt_a. \quad (36)$$

The unreserved channel time is treated as the server vacation time. The service system can be modelled as an M/G/1 queue with vacation and the average packet transmission delay can be found as

$$\mathrm{E}[D] = \mathrm{E}[\tau] + \frac{\lambda \mathrm{E}[\tau^2]}{2(1 - \lambda/\mathrm{E}[\tau])} + \frac{T_{CS} - T_r}{2}. \quad (37)$$

VI. NUMERICAL RESULTS

We consider a generic cluster with one CH and N sensors. The system setting is the same as described in Section II. For the bursty traffic, each sensor node generates one packet at the beginning of each CS interval with probability P_b. For the Poisson distributed traffic, the inter-arrival time between two consecutive packets generated by a given sensor is T_p. Default parameters are listed in Table I, where the default values of P_b and T_p are selected so that on average every sensor generates the same number of packets in the bursty arrival case and in the Poisson arrival case.

We first look at the delay performance for the system using PS. Figs. 4-5 all demonstrate very good match between the simulation and the analytical results. As shown in Fig. 4, packet transmissions experience shorter delay as C (number of channels) increases due to a lower outage probability, which is equivalent to more available channel time over a long term. When C is relatively small, increasing its value can reduce the average delay, especially when the traffic load is relatively high (large N). On the other hand, when C is larger than a certain value, such as 5 in the example shown in Fig. 4, further increasing it does not significantly decrease the average transmission delay. This is because the outage probability is sufficiently low, and further increasing C, even though may reduce the outage probability by several magnitudes, has very minor effect on the available channel time, and therefore does not affect much the transmission delay. Fig. 5 shows that the average packet transmission delay increases with N, and the delay increases more significantly when P_{on} is smaller.

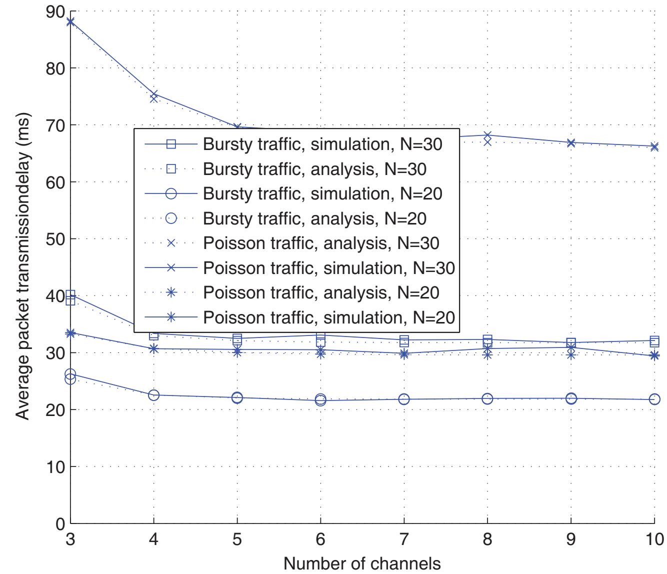

Fig. 4. PS: delay vs. number of channels.

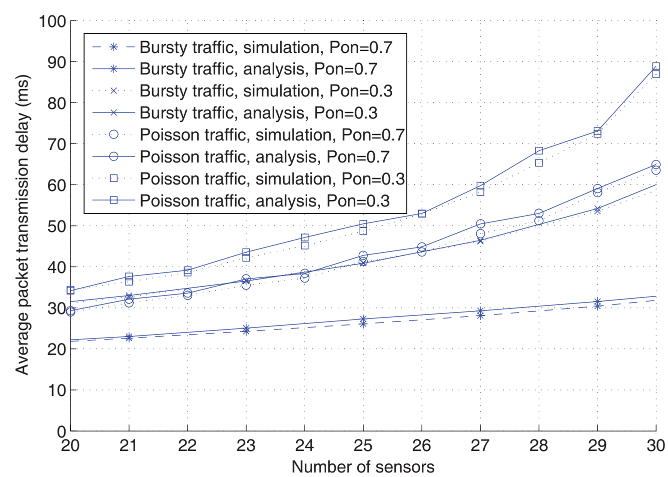

Fig. 5. PS: delay vs. number of sensors.

Figs. 4 and 5 both demonstrate that the bursty traffic in general experiences shorter average delay than the Poisson traffic for the system using PS. This is because in PS, the channel is more likely to be available in the earlier portion and unavailable in the later 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 available channel time in the current CS interval and have to be buffered for the rest of the 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 current CS interval.

We then consider the system using TS. Both Figs. 6 and 7 show that the analytical results are very close to the simulation

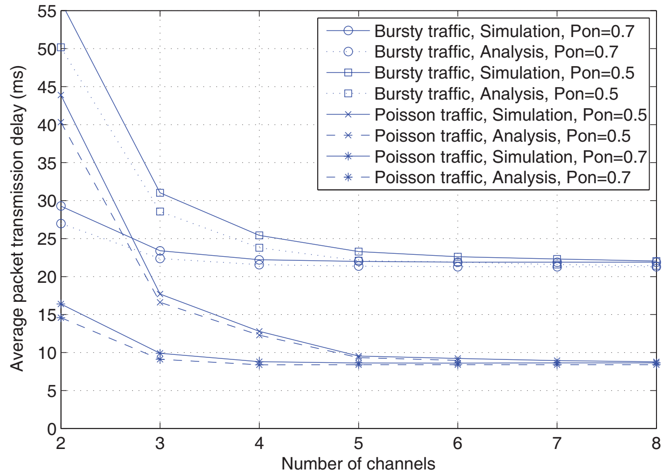

Fig. 6. TS: delay vs. number of channels.

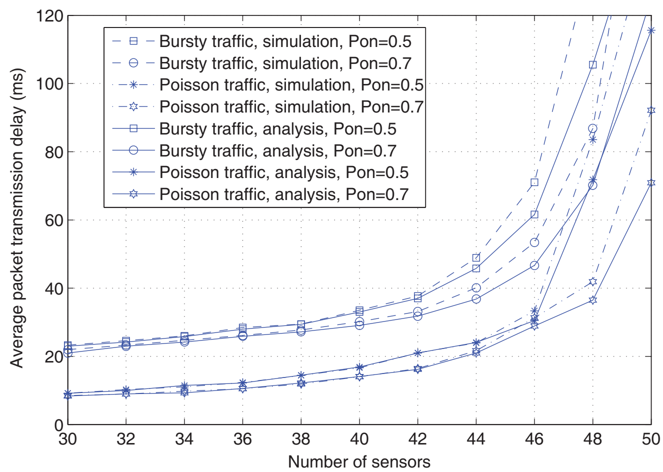

Fig. 7. TS: delay vs. number of sensors.

results, which indicates good accuracy of the analysis. The approximations made in the analysis do cause slight difference between the simulation and analysis when C is small and N is large. In deriving the mean delay for the bursty traffic, we arbitrarily moved all the time for packet transmissions before the COIs, and therefore the approximate delay is smaller than the actual delay. For the Poisson traffic, the service process within each CS interval is approximated to have a constant service rate, which results in shorter delay. When C is smaller, both the number of COIs and their average duration can be larger, and the approximation is less accurate. When the number of channels is larger, less COIs appear, and the approximation is more accurate. When N is larger, the buffer occupancy becomes higher, and the approximations cause more error.

Both Figs. 6 and 7 also show that using TS, the average transmission delay of the Poisson traffic is smaller than that of the bursty traffic. This is due to that the Poisson traffic does not have bursty arrivals. Packets can arrive at any time during a CS interval and be served at any time during the reserved time interval. This is opposite to the observation in the system using PS.

In general, using TS can achieve much shorter transmission

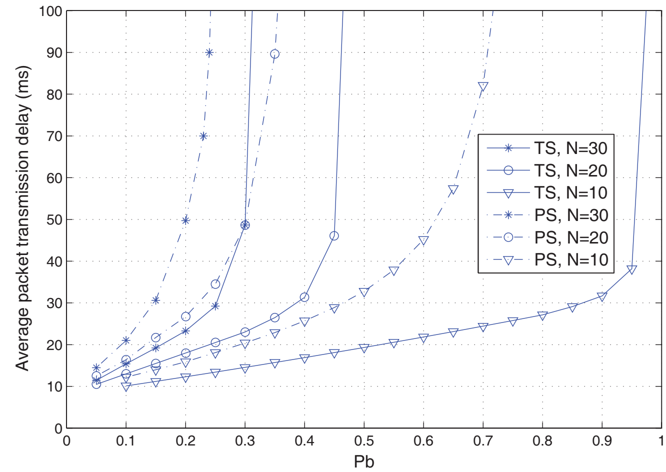

Fig. 8. Bursty traffic: delay vs. P_b.

delay than using PS. For example, when $N = 30$ and $P_{on} = 0.7$, the average transmission delay using PS is 32ms and 65ms, respectively, for the bursty traffic and the Poisson traffic as indicated in Fig. 5, and that using TS is 21ms and 10ms, respectively, for the bursty traffic and the Poisson traffic as indicated in Fig. 7. Further comparing the simulation results in Fig. 4 for PS and Fig. 6 for TS we can see that the delay decreases much faster with the number of channels in TS than that in PS, and this is true for both types of the traffic. This is because using TS the available channel time can be more effectively utilized for packet transmissions. While for PS, each CS interval can have at most one channel available interval. As long as the outage probability is sufficiently low so that a channel is available at the beginning of most CS intervals, the capacity of the system using PS is not affected much by further increasing C.

In Fig. 8 the delay performance of the bursty traffic is compared for the systems using PS and TS with varying P_b. As P_b increases, more packets are generated, and the average delay increases. If we keep the product of P_b and N to be the same (which gives the average number of packets generated in a CS interval), and vary P_b and N, for example, when $(P_b, N) = (0.2, 30)$, (0.3, 20), and (0.6, 10), respectively, the average transmission delay using PS is 50ms, 49ms, and 45ms, and using TS is 24ms, 22ms, and 21ms. This shows that the average delay is smaller for larger P_b and smaller N. The difference is more obvious for TS when P_bN is larger. For example, when $(P_b, N) = (0.3, 30)$, (0.45, 20), and (0.9, 10), the average transmission delay is 49ms, 42ms and 31ms, respectively. This is because the number of generated packets follows a binomial distribution, whose variance is $NP_b(1-P_b)$. When NP_b is fixed, a larger P_b results in smaller variance.

VII. Conclusions and Further Work

We have analyzed the performance of a cognitive radio sensor network for supporting real-time traffic. Our results indicate that satisfactory average packet transmission delay performance can be achieved for both bursty and Poisson traffic. Extending the current work to multi-cluster CRSN networks with both real-time and best effort traffic is underway. In the multi-cluster CRSN, data collected by the CHs from their associated sensors may traverse multiple hops in order to reach the sink, and both the intra-cluster traffic and the inter-cluster traffic share the available radio resources. Transmission delay for both real-time traffic and network capacity for real-time and best effort traffic will be studied.

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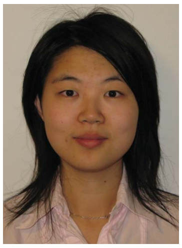
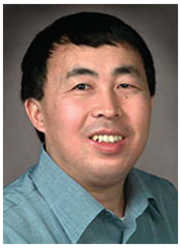
Zhongliang Liang received his B.E. degree from Huazhong University of Science and Technology, Wuhan, China in 2008 and MASc degree from McMaster University, Hamilton, Ontario, Canada in 2010. He is currently a Ph.D. candidate in Department of Computer Science and Engineering at Lehigh University, Bethlehem, PA, USA.



Shan Feng received the B.E. degree from Beijing University of Posts and Telecommunications, Beijing, China in 2007 and the MASc degree from McMaster University, Hamilton, Ontario, Canada in 2010, all in Electrical and Computer Engineering. Her research interests are in wireless sensor networks and cognitive radio networks.

Dongmei Zhao received the Ph.D degree in Electrical and Computer Engineering from the University of Waterloo, Waterloo, Ontario, Canada in June 2002. Since July 2002 she has been with the Department of Electrical and Computer Engineering, McMaster University, Hamilton, Ontario, Canada where she is an associate professor. Dr. Zhao's research interests include modeling and performance analysis, quality-of-service provisioning, access control and admission control in wireless communication networks. She has been an associate editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY since 2007. She also served as an editor for the *Journal of EURASIP Journal of Wireless Communications and Networking* and *Journal of Communication Networks*. She is a co-chair of the Wireless Networking Symposium in IEEE GLOBECOM 2007. Dr. Zhao is a member of IEEE and a Professional Engineer of Ontario.



Xuemin (Sherman) Shen received the B.Sc.(1982) degree from Dalian Maritime University (China) and the M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey (USA), all in electrical engineering. He is a Professor and University Research Chair, Department of Electrical and Computer Engineering, University of Waterloo, Canada. Dr. Shen's research focuses on resource management in interconnected wireless/wired networks, UWB wireless communications networks, wireless network security, wireless body area networks and vehicular ad hoc and sensor networks. He is a co-author of three books, and has published more than 400 papers and book chapters in wireless communications and networks, control and filtering. Dr. Shen served as the Technical Program Committee Chair for IEEE VTC'10, the Symposia Chair for IEEE ICC'10, the Tutorial Chair for IEEE ICC'08, the Technical Program Committee Chair for IEEE Globecom'07, the General Co-Chair for Chinacom'07 and QShine'06, the Founding Chair for IEEE Communications Society Technical Committee on P2P Communications and Networking. He also served as a Founding Area Editor for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS; Editor-in-Chief for *Peer-to-Peer Networking and Application*; Associate Editor for IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY; *Computer Networks*; and *ACM/Wireless Networks*, etc., and the Guest Editor for IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, *IEEE Wireless Communications*, *IEEE Communications Magazine*, and *ACM Mobile Networks and Applications*, etc. Dr. Shen received the Excellent Graduate Supervision Award in 2006, and the Outstanding Performance Award in 2004 and 2008 from the University of Waterloo, the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. Dr. Shen is a registered Professional Engineer of Ontario, Canada, an IEEE Fellow, and a Distinguished Lecturer of IEEE Communications Society.