Delay minimization by adaptive framing policy in cognitive sensor networks

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***Abstract*—In this paper, a delay-minimal joint framing and scheduling policy is proposed for cognitive sensor networks, where a secondary sensor node collects measurement samples, combines them together into packets and transmits the packets to a central data fusion center after proper scheduling, when a shared channel is released by primary nodes.**

The main objective of this study is to minimize the end-to-end delivery time for secondary sensor nodes based on the current input traffic rate, channel availability process and channel bit error probability. The proposed method outperforms conventional constant-length framing policies for any choice of packet length by minimizing the delay and preventing potential queue instability under dynamic channel conditions. This method can be utilized by secondary nodes in a wide variety of wireless sensing applications in order to collect time-sensitive data with minimal delays[1].

I. Introduction

Transmission delay minimization has gained considerable attention recently due to emerging delay-constrained wireless sensing applications [1], [2]. This requirement is even more crucial in cognitive radio networks (CRN) for low-priority secondary nodes due to an additional waiting time to access the shared channel [3].

The majority of delay minimization efforts are devoted to develop optimal routing and scheduling policies in the MAC layer. Hence, the impact of physical layer parameters is frequently overlooked [4], [5]. In fact, the delay associated with each transmission link is considered as out of one's control and a fixed parameter in the majority of delay optimal networking problems [6].

In this paper, we revisit this perspective and aim at minimizing the overall delay by adjusting packet lengths based on the current physical layer conditions. Packet lengths affect transmission delay by regulating several transmission parameters such as packet overhead ratio, packet drop rate, packet inter-arrival times and queuing dynamics.

The idea of local packet length adjustment in order to maximize the network throughput in WLAN channels is introduced in [7]. In this work, the impact of packet lengths on the transmission delay is studied for the secondary nodes in CRN under opportunistic channel access. We characterize the end-to-end delay comprising of various delay terms including packet formation delay, waiting time in the send buffer, waiting time to find spectrum holes and the actual transmission time including potential retransmissions. The proposed policy minimizes the transmission delay for secondary nodes and prevents queue instability in dynamic channel conditions, while the primary nodes remain unaffected. More specifically, the expected overall transmission delay is minimized by adjusting the number of measurement samples combined into packets based on the sensing rate, statistics of channel utilization by primary nodes and the shared channels bit error rate.

II. System Model

The system model consists of primary and secondary transmitter-receiver pairs sharing the same channel, as depicted in Fig. 1. We deploy the interweave cognitive transmission with a perfect Channel State Information (CSI) assumption, such that the secondary transmitter seizes the channel only if it is not in use by the primary transmitter.

A. Framing method

The secondary node consists of the sensing and wireless transmission modules. A sequence of N-bit measurement samples $\{X_i\}_{i=0}^{\infty}$ are generated by the sensing module according to a Poisson process with rate λ. The samples are combined into packets with a constant header size H and scheduled for transmission through a channel with rate R_{ch}, as depicted in Fig. 1a.

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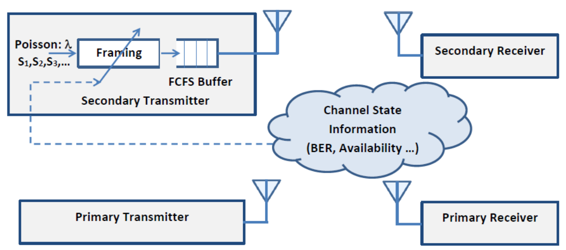
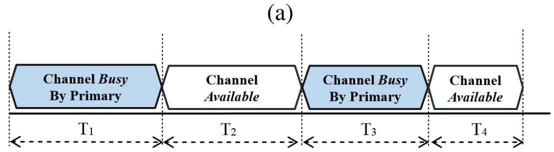


(a)



(b)

Fig. 1: (a): System model, (b): Channel availability process.

We develop a *Number-based framing policy*, such that the communication module waits for the arrival of k samples $\{X_{i_1}, X_{i_2}, \ldots, X_{i_k}\}$ and then encapsulates them into a single packet P_i. Therefore, each packet includes $L(k) = kN + H$ bits.

In order to fully determine the packet arrival process, we need to obtain the distribution of the packet inter-arrival times denoted by τ_i, which is the summation of k independent exponentially distributed random variables ($\tau_i = \zeta_{(i-1)k+1} + \zeta_{(i-1)k+2} + ... + \zeta_{ik}$), where ζ_j is the inter-arrival time between symbols X_{j-1} and X_j. Using the Moment Generating Function (MGF), we obtain the Gamma distribution for packet inter-arrival times as follows:

$$f_\tau(\tau) = \text{Gamma}(\tau; k, \lambda) = \frac{\lambda^k t^{k-1}}{\Gamma(k)} e^{-\lambda\tau}, \ \tau > 0, \quad (1)$$

where $\Gamma(k)$ is the Gamma function and equals $(k-1)!$ for integer-valued k. The coefficient of variation of τ is denoted by C_τ and is evaluated as follows:

$$\mathbb{E}[\tau] = \frac{k}{\lambda}, \quad \sigma_\tau^2 = \frac{k}{\lambda^2} \Longrightarrow C_\tau = \frac{\sigma_\tau}{E[\tau]} = \frac{1}{\sqrt{k}}. \quad (2)$$

B. Scheduling policy

The packets are queued in an infinite-length send buffer with a *best effort* FCFS scheduling discipline and automatic repeat request (ARQ) retransmission mechanism. We take the commonly accepted model of Poisson process for channel utilization by primary nodes as depicted in Fig. 1b. In other words, the time is split into consecutive intervals denoted by $T_i, i = 1, 2, \ldots$ with alternating channel states (*busy* and *available*), where the busy and available intervals are exponentially distributed with mean values of u and v, respectively (i.e. $T_i \sim \text{expo}(u)$ for $i = 1, 3, \ldots$ and $T_i \sim \text{expo}(v)$ for $i = 2, 4, \ldots$). Noting the memory-less property of Poisson process, the secondary node starts transmitting its packet if the channel is available no matter how much time passed since the last channel utilization by the primary node.

III. Delay Analysis

In order to obtain delay-minimal policy, we quantify various delay terms for the developed system model.

1) **Average packet formation time:** This is the time a sample experiences before it is bundled into a packet. Considering the Poisson process for sample arrivals, we obtain the following expected value for the averaged packet formation delay for samples that form packet P_i:

$$\mathbb{E}[\bar{F}_i] = \frac{1}{k}\mathbb{E}\Big[\sum_{j=1}^{k}(k-j)\zeta_{(i-1)k+j}\Big]$$

$$= \frac{1}{k}\Big[\sum_{j=1}^{k}(k-j)\mathbb{E}[\zeta_{(i-1)k+j}]\Big] = \frac{k(k-1)}{2k}\mathbb{E}[\zeta] = \frac{k-1}{2\lambda},$$

where ζ_j is the inter-arrival time between samples $j-1$ and j. This equation holds for all packets due to the memoryless property of sample arrival process, so we have:

$$\mathbb{E}[\bar{F}] = \mathbb{E}[\bar{F}_i] = \frac{k-1}{2\lambda}.$$

2) **Service time:** A successful transmission of a packet may include sending multiple copies due to transmission errors. We first characterize service time for sending one copy denoted by $S1$. There are two scenarios for a packet when it reaches the queue frontier and becomes ready for transmission. In case 1, the packet confronts the channel at its available state, hence transmission initiates immediately. For case 1, service time SV is the required time to transmit a single copy denoted by $s_1 = \frac{L}{R_{ch}} = \frac{kN+H}{R_{ch}}$, where R_{ch} is the channel rate. Therefore, SV is a deterministic function of system parameters with probability density function (pdf) $f_{SV}(s) = \delta(s - s_1) = \delta(s - \frac{kN+H}{R_{ch}})$. In case 2, the packet P_i meets a busy interval, hence waits for a random time Ω_i to meet the next available interval (i.e., $SU_i = s_1 + \Omega_i$). Noting the memoryless property of exponential distribution for intervals T_i, Ω_i can be viewed as a portion of T_i if it is split uniformly (i.e. $\Omega_i | T_i = t \sim \text{Uniform}(0, t)$). Distribution of Ω is obtained by marginalizing out T as follows:

$$f_\Omega(\omega) = \int_{t=0}^{\infty} f_{\Omega_i|T}(\omega|t) f_T(t) dt$$
$$= \int_{t=0}^{\infty} \frac{U_\omega(t) - U_\omega(0)}{t} \frac{1}{u} e^{-t/u} dt \quad (3)$$

Service time for case 2 is $f_{SU}(s) = f_{\Omega}(s - \frac{kN+H}{R_{ch}})$. Case 1 and 2 occur with probability $\frac{v}{u+v}$ and $\frac{u}{u+v}$, respectively. Therefore, the pdf of $S1$ is a bimodal distribution with the following components:

$$f_{S1}(s) = \frac{v}{u+v} f_{SV}(s) + \frac{u}{u+v} f_{SU}(s). \tag{4}$$

The 1st and 2nd moments of $S1$ is obtained from equs (3) and (4) after some manipulations as follows:

$$\begin{aligned}
\mathbb{E}[S1] &= \frac{v}{u+v}\mathbb{E}[SV] + \frac{u}{u+v}\mathbb{E}[SU] \\
&= \frac{v}{u+v}s_1 + \frac{u}{u+v}(s_1 + \frac{u}{2}) = s_1 + \frac{u^2}{2(u+v)} \\
\mathbb{E}[S1^2] &= \frac{v}{u+v}\mathbb{E}[(SV^2] + \frac{u}{u+v}\mathbb{E}[(SU^2] \\
&= \frac{v}{u+v}(s_1)^2 + \frac{u}{u+v}\big[(s_1)^2 + \frac{2u^2}{3} + us_1\big]
\end{aligned} \tag{5}$$

Now, we consider the impact of retransmissions. For zero error tolerance, a packet transmission is checked at the destination by error detection codes (e.g. CRC) and considered successful if no bit is flipped during transmissions. This occurs with success probability $\alpha_P = 1 - \beta_P = \alpha^{kN+H} = (1-\beta)^{kN+H}$, where β is the bit error probability. Re-transmission of a packet is continued until one copy successfully reaches the destination, therefore the number of transmission r follows a Geometric distribution with success parameter $\alpha_P = 1 - \beta_P$:

$$\begin{aligned}
\mathbb{P}r(R=n) &= (\beta_P)^{n-1}(1-\beta_P) \\
&= \big[(1-\beta)\beta^{n-1}\big]^{kN+H}.
\end{aligned} \tag{6}$$

The service time including potential re-transmissions is $S = \sum_{i=1}^{R} S_i$, where S_i and R are independent random variables distributed according to (4) and (6), respectively. Therefore, we have the following expressions for the moments of service time:

$$\begin{aligned}
\mathbb{E}[S] &= \mathbb{E}_R\big[\mathbb{E}_{S|R}[S|R]\big] = \mathbb{E}_R\big[\mathbb{E}_{S|R}[\sum_{i=1}^{R} S_i|R]\big] \\
&= \mathbb{E}_R\big[R\mathbb{E}_{S_i|R}[S_i|R]\big] = \mathbb{E}_R[R]\ \mathbb{E}_{S_i}[S_i] \\
&= \frac{1}{\alpha_P}\big(s_1 + \frac{u^2}{2(u+v)}\big),
\end{aligned} \tag{7}$$

$$\begin{aligned}
\mathbb{E}[S^2] &= \mathbb{E}_R\big[\mathbb{E}_{S|R}[S^2|R]\big] \\
&= \mathbb{E}_R\big[\sum_{i=1}^{R}\mathbb{E}_{S_i}[S_i^2] + 2\sum_{i=1}^{R}\sum_{j=1,j\neq i}^{R}\mathbb{E}[S_i]\mathbb{E}[S_j]\big] \\
&= \mathbb{E}_R\big[R\mathbb{E}[S_i^2] + R(R-1)(\mathbb{E}[S_i])^2\big] \\
&= \mathbb{E}[R]\mathbb{E}[S_i^2] + \mathbb{E}[R(R-1)](\mathbb{E}[S_i])^2 \\
&= \frac{1}{\alpha_P}\Big[\frac{v}{u+v}(s_1)^2 + \frac{u}{u+v}\big[(s_1)^2 + \frac{2u^2}{3} + us_1\big]\Big] \\
&+ \frac{2\beta_P}{(\alpha_P)^2}\Big[s_1 + \frac{u^2}{2(u+v)}\Big]^2
\end{aligned} \tag{8}$$

where we used pairwise independence of S_i, as well as their independence from R.

3) **Waiting time:** Another delay term is waiting time in the transmit buffer, denoted by W. Here, we use the celebrated Kingman formula, which approximates the expected waiting time for a GI/GI/1 queuing system provided that the service time and packet inter-arrival times are independent [8]. This condition holds for the proposed scenario. Packet inter-arrival times are Gamma distributed and depend solely on the measurement sample generation rate λ for a given k, whereas service time for any choice of k is independent of sample arrival process. Simply speaking, once the number of samples in each packet, k is selected, service time is influenced solely by the channel error rate and channel requests by primary nodes. Therefore, the arrival process is totally independent from the service process and hence we can use the Kingman equation as follows:

$$\mathbb{E}[W] \approx \frac{\rho}{(1-\rho)}\frac{\mathbb{E}[S](C_S^2 + C_\tau^2)}{2}, \tag{9}$$

where ρ is the queue utilization factor defined as $\rho = \mathbb{E}[\mathbf{s}]/\mathbb{E}[\tau] = \frac{\lambda}{k\alpha_P}\big(s_1 + \frac{u^2}{2(u+v)}\big)$. C_S and C_τ denote the coefficient of variation for service time S and packet inter-arrival time τ, respectively.

Substituting the required moments obtained from equations (2), (7) and (8) in (9), we have the following approximate expected waiting time:

$$\begin{aligned}
\mathbb{E}[W] &\approx \frac{\rho}{(1-\rho)}\frac{\mathbb{E}[S](C_S^2 + C_\tau^2)}{2} \\
&= \frac{\lambda^2 M^2}{2\alpha_P^2 K^2 - 2\alpha_P K\lambda M}(1 - 2\alpha_P + \frac{N\alpha_P}{M^2} + \frac{1}{k})
\end{aligned} \tag{10}$$

where we have:

$$M = s_1 + \frac{u^2}{2(u+v)},\ N = \big(s_1\big)^2 + \frac{u}{u+v}\big(\frac{2u^2}{3} + us_1\big). \tag{11}$$

IV. Optimal Framing Interval

The expected end-to-end delay D_j for k measurement sample X_j bundled into packet P_i comprises the above mentioned delay terms as:

$$E[D_j] = E[\bar{F}_i] + E[W_i] + E[S_i], \quad \text{for } 1 + (i-1)k \le j \le ik \qquad (12)$$

Under stability conditions for stationary queuing system ($\rho < 1$), the expected delay of the samples are equal ($\mathbb{E}[D] = \mathbb{E}[D_i]$) and we have:

$$\mathbb{E}[D] = \mathbb{E}[\bar{F}] + \mathbb{E}[W] + \mathbb{E}[S] \approx \frac{k-1}{2\lambda} + \frac{M}{\alpha_P} + \frac{\lambda^2 M^2}{2\alpha_P^2 K^2 - 2\alpha_P K \lambda M}(1 - 2\alpha_P + \frac{\alpha_P N}{M^2} + \frac{1}{k}) \qquad (13)$$

Equation in (13) provides a closed form expression for the expected sample end-to-end delay, $\mathbb{E}[D]$ in terms of framing parameter k, noting that $\alpha_P = (1-\beta)^{kN+H}$ and $s_1 = \frac{kN+H}{R}$ are functions of k. The rest of the parameters are either i) constant system setting (such as N and H), which are defined by the application of interest or ii) dynamic system conditions (such as channel error probability β and channel availability parameters u and v), which can be estimated using training techniques.

Therefore, minimizing (13) with respect to k provides a framing policy with minimal expected average delay under given conditions. For slow-varying channels, this method can be used to adaptively adjust packet lengths for the secondary nodes based on the channel conditions as well as the primary node channel utilization statistics. Minimizing equation (13) with respect to k can be easily solved using numerical methods or by extensive search.

V. Simulation Results

In this section, the simulation results are presented to verify the accuracy of derived expressions and examine the delay performance of the proposed method for a system composed of multiple primary nodes and a single secondary sensor node communicating with its target destination.

The measurement samples are generated according to a Poisson process with rate $\lambda = 30$. In order to obtain the statistical means of the waiting time, we take the average over only 50% of the packets that are later in order to assure that the queue is already stabilized and the transition period is passed. We investigate both conventional (full channel access) and cognitive sensor scenarios. The rest of parameters are set as $\lambda = 30$ samples/second, $N = 8$ bits, and $H = 64$ bits, unless specified otherwise.

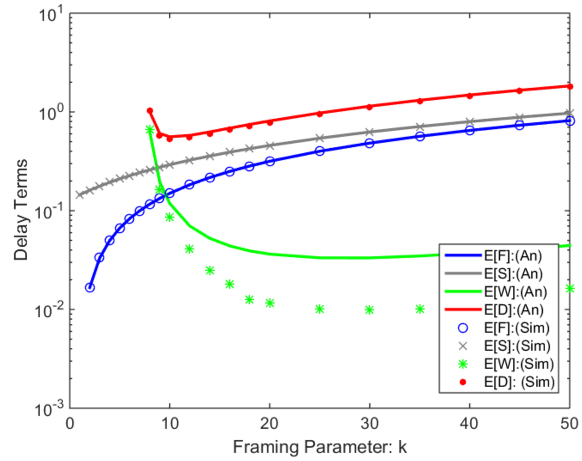


Fig. 2: Comparison between the simulations and analytical derivations for different delay terms under full channel access and error probability $\beta : 10^{-4}$

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Fig. 2 presents variations of different expected delay terms ($\mathbb{E}[F]$, $\mathbb{E}[S]$, $\mathbb{E}[W]$ and $\mathbb{E}[D]$) due to the choice of framing parameter k for the full channel access scenario ($u/v \rightarrow 0$). The average packet formation delay $\mathbb{E}[\bar{F}]$ (blue curve) is an increasing function of k, since the measurement samples wait for more subsequent samples to form a single packet. Similarly, increasing k results in longer packets, which in turn increases the expected service time $\mathbb{E}[S]$. The rate of variations of S is lower than the one of τ, since S contains two parts, a constant time to transmit H header bits regardless of the choice of k, and a variable part to transmit kN information bits. Moreover, k affects the service time by impacting packet drop rate. On the other hand, the system utilization factor $\rho = \frac{\mathbb{E}[S]}{\mathbb{E}[\tau]}$ decreases with k and hence the packets experience shorter waiting times in the queue. This implies that the expected waiting time $\mathbb{E}[W]$ declines as k increases (green curve). Therefore, the expected end-to-end delay $\mathbb{E}[D]$ demonstrates a valley-shaped functionality with respect to k, meaning that there is an optimal value for k that minimizes the overall delay. The simulation results reflect a perfect match between the simulations results and the analytical derivations. The minor mismatch for waiting time corresponds to the well-known approximation in the Kingman formula (green curve).

The impact of channel quality on the end-to-end delay is demonstrated in Figs. 3 and 4. The channel quality is represented with bit error probability β. As β increases, the re-transmission rate due to packet error increases, which in turn causes a shift in the expected end-to-

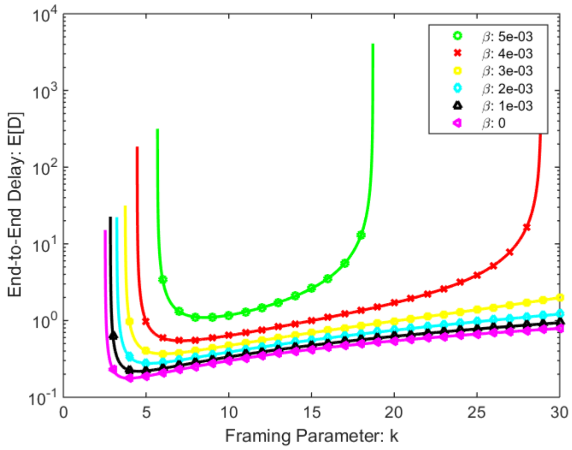

Fig. 3: Comparison of the average delay of the proposed adaptive framing polic with fixed packeting policies.

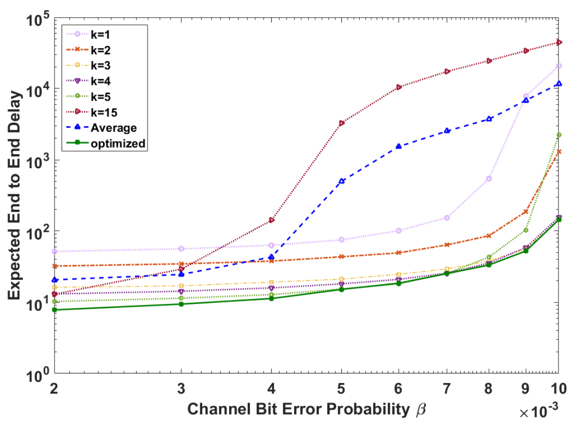

Fig. 4: Impact of the channel quality on the optimal framing policy. $\mathbb{E}[D]$ is plotted versus framing parameter k for different channel error probabilities β.

end delay. This effect is higher for larger k values for zero error tolerance system. This suggests that adjusting the framing parameter k with channel error rate can dramatically reduce the transmission delay. The optimal framing number for different channel error rates for a given system parameters is presented in table I. For instance, for a transmission system with parameters ($\lambda = 30$ bits, $N = 8$ bits, $H = 64$ bits, $R_{ch} = 1500$ bits/sec), if the channel bit error probability is 4×10^{-3}, the optimal framing policy is combining each $k = 7$ consecutive samples into a single transmission packet.

Fig. 4, compares the resulting expected delay for the proposed system and the systems with fixed framing policies. In this experiment, the channel is split into consecutive segments with random bit error probabilities

TABLE I: Optimal framing parameter versus channel quality. Channel rate is $R_{ch} = 1500$.

Channel Error Prob. β	Optimal Framing Parameter: k
$\beta < 8.4 \times 10^{-4}$	4
$8.4 \times 10^{-4} \leq \beta < 2.4 \times 10^{-3}$	5
$2.4 \times 10^{-3} \leq \beta < 3.5 \times 10^{-3}$	6
$3.5 \times 10^{-3} \leq \beta < 4.3 \times 10^{-3}$	7
$4.3 \times 10^{-3} \leq \beta < 5.0 \times 10^{-3}$	8
$5.0 \times 10^{-3} \leq \beta < 5.7 \times 10^{-3}$	9
$5.7 \times 10^{-3} \leq \beta$	10

ranging from $\beta = 2 \times 10^{-3}$ to $\beta = 10^{-2}$. The proposed system with adaptive number of symbols in packet, k outperforms the conventional fixed-length policies for any choice of k.

Fig. 5 presents the behavior of expected service time $\mathbb{E}[S]$ with varying channel unavailability factor $\rho_{ch} = \frac{u}{v}$ for sensors acting as secondary nodes in the CRN under the proposed joint framing and scheduling policy elaborated in section II. For a small ρ values, the system approaches the conventional communications systems with full channel access. Therefore, service time for a packet of length $kN + H$ increases with k. However, for a high ρ_{ch} values, a large portion of service time is devoted to waiting until the busy channel is released by the primary nodes, therefore $\mathbb{F}[S]$ is proportional to ρ_{ch} as shown in Fig. 5.

The impact of channel availability on the end-to-end delay is depicted in Fig. 6. It is shown that for high ρ_{ch} values, the channel is rarely accessible to the secondary

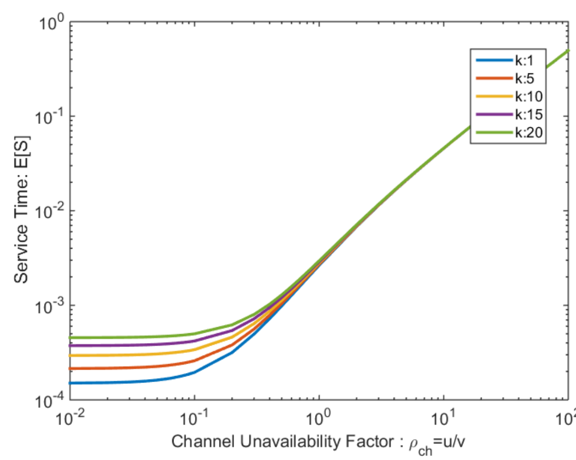

Fig. 5: Service time $\mathbb{E}[S]$ is plotted versus framing parameter k for different channel unavailability factor $\rho_{ch} = \frac{u}{u+v}$. ($\beta_D = \beta_H = 10^{-6}$, $R_D = R_H = \frac{1}{2}$, $R_{ch} = 10^6$.)

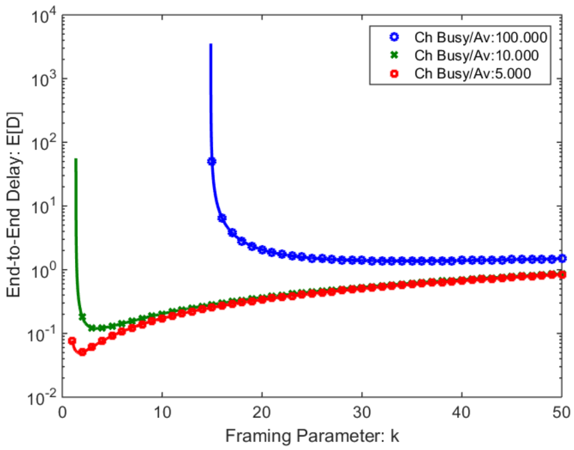

Fig. 6: Impact of the channel availability on $\mathbb{E}[D]$ for different channel unavailability factor $\rho_{ch} = \frac{u}{u+v}$. Simulation parameters are the same as Fig. 5

node and hence the effective channel rate is lower. Therefore, for a given information rate λN, a higher number of samples in a packet is required to decrease the overhead cost $\eta = \frac{H}{KN}$, so that the effective input bit rate $\lambda N(1+\eta)$ falls below the channel's affordable rate. For instance, for $\rho_{ch} \geq 100$, the queue becomes unstable for $k < 15$ under given parameters (red curve). As the channel utilization by the primary node approaches zero ($\rho_{ch} \rightarrow 0$), the delay behavior approaches the conventional system parameters depicted in Fig. 3.

VI. Concluding Remarks

In this paper, an implementation of cognitive sensor networks is studied, where a secondary sensor nodes monitors a shared channel primarily owned by primary users and transmits its measurements to a designated destination. An optimal scheduling policy is proposed under the assumption of alternating available and busy channel intervals, where both states are exponentially distributed. Under this policy, a packet transmission initiates as soon as the channel becomes available after departure of the preceding packets in the queue. The packet transmission may be interrupted by channel requests by the primary users. The packets are also dropped if an information bit is flipped due to channel errors. In both cases the transmission is postponed to the first interval with an available channel state. A number-based framing policy followed by a FCFS queuing system is proposed for such a system and a closed-form expression is derived to relate the end-to-end transmission delay to the system parameters (such as input sample rate λ, packet header cost $\eta(k) = \frac{kN}{kN+H}$, channel coding rate R_D, R_H) as well as the channel parameters (such as channel rate R_{ch}, bit error probability β and channel utilization rate by primary nodes ρ_{ch}). This formulation provides an optimal value for the number of samples at each packet as a key framing parameter. This suggests that the current method of using constant packet lengths ignoring the underlying physical layer conditions is extremely inefficient; since it not only may dramatically increase the transmission delay, but also may make the queuing system unstable under some channel conditions.

This proposed joint framing-scheduling policy can be used by any cognitive sensor network in order to minimize the transmission delays under given system quality factors. If the channel variation is much slower than the single packet transmission time, this scheme can also be used to adaptively adjust the framing parameter k time-varying shared channels. Including learning techniques to train the channel utilization process by primary nodes will eliminate the need for full channel state information and will generalize the proposed method for a wider range of cognitive wireless sensor systems.

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