Delay minimization through adaptive framing policy in cognitive sensor networks

Abstract—**In this paper, we study the end-to-end delay for cognitive sensor networks, where a secondary sensor node collects measurement samples and transmits them to a central data fusion center, when a shared channel is not utilized by primary nodes. We model the shared channel status by alternating busy and vacant intervals which are exponentially distributed with different mean values.**

We characterize the end-to-end delay for the secondary nodes by accounting for various delay terms including the packet formation time, the actual transmission time, waiting time in the queue and waiting time for the channel to become available. This characterization enables us to develop a delay-minimal packet formation and scheduling policies for the secondary node by regularizing the packet lengths under the given system parameters, while the primary nodes remain unaffected. The proposed methodology can be utilized by secondary nodes in a wide variety of wireless sensing applications in order to collect time-insensitive data with minimal delays.

Index Terms—**Framing policy, cross-layer optimization, channel adaptation, delay analysis, queuing systems.**

I. Introduction

An important quality factor in wireless sensing system is transmission delay. Therefore, minimizing transmission delay as well as optimizing other transmission performance indicators under delay constraints has gained considerable attention recently [1]–[3]. More specifically, in delay sensitive sensor networks, the information is valid only of the age of information remains below a certain limit [4], [5]. Delay minimization is a more demanding requirement in Cognitive Radio Networks (CRN) for the low-priority secondary sensor nodes due to an additional waiting time to seize the channel [6], [7]. For instance, in an interweave based CRN implementation, secondary nodes experience higher delays to find spectrum holes not utilized by primary nodes [8], [9].

In this paper, we develop a delay-minimal joint framing and scheduling policy for cognitive sensor networks, where the secondary sensor nodes collect their measurements, bundle them into packets, buffer them in a First Come First Serve (FCFS) queue and transmit them into a central processing unit without causing interference to the primary users.

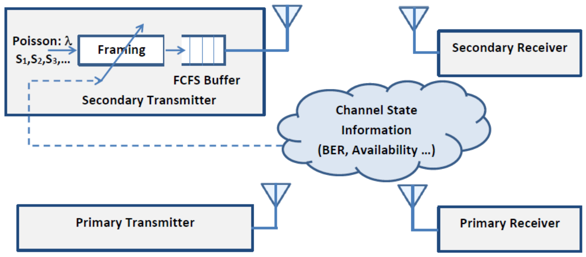
In the majority of delay minimization techniques, the main efforts is devoted to developing optimal routing and scheduling policies in the network and MAC layers, hence the impact of physical layer parameters is largely overlooked [10]–[12]. In fact, in most routing and scheduling algorithm designs, the delay associated with each link is considered as an out of control fixed parameter [13], [14].

Packets lengths can have crucial impacts on the communication systems performance in terms of throughput and delay [15]–[17]. For instance, the idea of local packet length adaptation to maximize the overall throughput in wireless local area networks (WLAN) is introduced in [18]. Packet lengths severely affect the transmission delay by regulating several transmission parameters such as packet overhead ratio, packet drop rate, packet inter-arrival times and queuing dynamics. The impact of packet lengths on the transmission delay is studied in [19] and a time-based delay minimal framing policy is proposed to optimally group information samples into packets such that the transmission delay is minimized under given physical layer conditions. In this work, we extend this method and propose a joint framing-scheduling policy for interweave-based cognitive sensor networks, such that the secondary node's transmission delays is minimized while the primary nodes remain unaffected. In this policy, we minimize the expected end-to-end transmission delay by adjusting the number of samples combined into packets based on the statistics of channel utilization by primary nodes as well as the shared channels error rate.

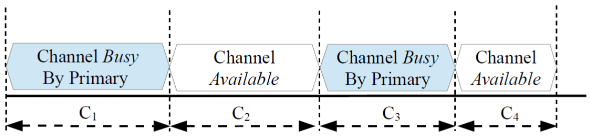
The proposed joint framing and scheduling policy not only minimizes the secondary node's transmission delay, but also prevents a potential queuing system instability for a given system configuration, quality factors and traffic statistics. In case of slow channel variations, this scheme is almost delay-optimal and can replace the current inefficient fixed-length packet framing policies. In the proposed method, delay optimality is achieved by adaptively adjusting packet lengths based on the current channel state information. The rest of this paper is organized as follows. In section II, the system model along with the proposed joint framing and scheduling policy is presented. In section III, a concrete closed form expression is derived for the secondary node's transmission delay under the proposed method. In section IV, simulation results are provided to verify the optimality of the proposed method followed by concluding remarks in section V.

II. System Model

The system model consists of two primary and secondary transmitter-receiver pairs sharing the same channel, as depicted in Fig. 1. The primary transmitters access the channel to send their packets regardless of the secondary nodes presence. We take the interweave-based cognitive transmission approach with a perfect Channel State Information (CSI) assumption, such that the secondary transmitter listens to the channel and seizes the channel only if it is not in use by the primary transmitters. As soon as a primary transmitter seizes the channel to transmit his packet, the secondary transmitter stops transmitting his current packet



(a)



(b)

Fig. 1: System model: (a) The secondary sensor node collects the measurement samples, combines them into packets with constant header sizes and buffers them in a FCFS queue for opportunistic transmission through the shared channel. (b) The time axis is split into intervals with alternating busy and available channel states.

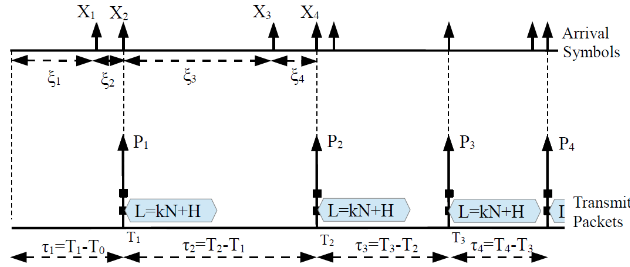


Fig. 2: Number-based *framing policy*: Sensor measurements $\{X_j\}_j = 1^\infty$ are generated according to a Possion process with rate λ. The sample inter-arrival times ζ_j are exponentially distributed with mean $1/\lambda$. Each k consecutive samples $\{X_{(i-1)k}, X_{(i-2)k}, \dots, X_{ik}\}$ are bundled into a packet P_i at time T_i. The scenario is depicted for $k = 2$.

and leaves the channel to avoid interference. Therefore, the secondary node is totally absent from the primary user's perspective. We use automatic repeat request (ARQ) retransmission mechanism and retry transmitting packets until an error-free copy is delivered to the destination.

A. Framing method

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. Therefore, the sample inter-arrival times denoted by ξ_j are independent and exponentially distributed random variable with mean $1/\lambda$. The secondary node combines the samples into packets with a constant header size H, schedules the packets in an infinite-length buffer with a FCFS service discipline for transmission through the shared wireless channel with bit rate R to its designated destination, as depicted in Fig. 1a.

We develop a *Number-based framing policy*, such that the sensor node waits for arrival of k samples $\{X_{k(i-1)+1}, X_{k(i-1)+2}, \dots, X_{ki}\}$ and then encapsulates them into a single packet P_i as shown in Fig. 2. Therefore, each packet includes $L(k) = kN + H$ bits, where k is an adjustable framing parameter.

In order to fully determine the packet arrival process, we also need to obtain the distribution of the packet inter-arrival times denoted by τ_i. We note that the packet inter-arrival time is the summation of k consecutive sample inter-arrival times (i.e. $\tau_i = T_i - T_{i-1} = \sum_{j=1}^{k} \xi_{i_j}, \xi_j \sim \exp(\xi; 1/\lambda)$). The Moment Generating Function (MGF) for an exponentially distributed random variable ξ is $M_\xi(t) = \mathbb{E}[e^{t\xi}] = \frac{\lambda}{\lambda - t}$. Therefore, the MGF of τ_i is $M_{\tau_i}(t) = \mathbb{E}[e^{t\tau_i}] = M_{\xi_1}(t) \times \dots \times M_{\xi_k}(t) = \big(M_\xi(t)\big)^k = (\frac{\lambda}{\lambda - t})^k$, which corresponds to a Gamma distribution with shape parameter k and rate parameter λ. Therefore, we have

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

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

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

This parameter is used in calculating the waiting time for the utilized queuing system in section III-C.

B. Scheduling policy

Here, we assume that the channel access by the primary network users follows a Poisson process. In other words, the time axis is split into consecutive intervals denoted by $C_i, i = 1, 2, \dots,$ with alternating channel states. During the odd intervals, the channel is utilized by the primary nodes and hence the channels appear *busy* or *unavailable* to the secondary nodes. The even intervals correspond to the channel availability for the secondary nodes, hence called *available* or *vacant*. For the sake of brevity, we call the intervals with *busy* and available channel states as *busy intervals* and *available intervals*. The odd and even intervals both are exponentially distributed with different mean values of u and v, respectively as follows:

$$f_{C_i}(c) = \begin{cases} \exp(c; u) = \frac{1}{u} e^{-c/u} & i = 1, 3, 5, \dots, \\ \exp(c; v) = \frac{1}{v} e^{-c/v} & i = 2, 4, 6, \dots. \end{cases} \quad (3)$$

The channel unavailability factor is defined as the ratio of busy interval mean time to the available interval mean time $\rho_{ch} = \frac{u}{v}$. The assumption of exponential distribution for channel access process is consistent with the commonly adopted distribution for service time in communication systems. This assumption also simplifies the operation of the secondary nodes due to its memoryless property, which implies

$$\mathbb{P}r(C_i > t + \alpha | C_i > \alpha) = \mathbb{P}r(C_i > t) = e^{-t/v}, \\ \text{for } i = 2, 4, 6, \dots \ . \quad (4)$$

In other words, if the channel was available for α seconds, once the secondary node intends a packet transmission, the probability of extension of the channel availability for additional t seconds is independent of α. An immediate consequence of this property is that the secondary node starts transmitting its packet if the channel is available no matter how long passed since the last channel utilization by the primary nodes. This simplifies the scheduling policy and the subsequent queuing system analysis as follows next.

III. Delay Analysis

In order to obtain delay-minimal policy, we quantify different delay terms under developed system model.

A. Packet formation time

The first delay source is the time that measurement samples spend until the encapsulating packet is formed (Fig. 2). According to the framing method described in section II-A, the inter-arrival time between samples $j-1$ and j is ζ_j, therefore a sample $X_j,\ (i-1)k+1 \leq j \leq ki$ experiences packet formation delay of $\sum_{l=j+1}^{ik} \zeta_l$. The average of this delay over all samples of the packet P_i, denoted by $\bar{F}_i$, is calculated as

$$\bar{F}_i = \frac{1}{k} \sum_{j=(i-1)k+1}^{ik} \left(\sum_{l=j+1}^{ik} \zeta_l \right). \tag{5}$$

After some rearrangements, we obtain the following expected value for the averaged packet formation delay:

$$\begin{aligned} \mathbb{E}[F] &= \mathbb{E}[\bar{F}_i] = \frac{1}{k}\mathbb{E}\Big[\sum_{j=1}^{k}(k-j)\zeta_{(i-1)k+j}\Big] \\ &= \frac{1}{k}\Big[\sum_{j=1}^{k}(k-j)\mathbb{E}[\zeta_{(i-1)k+j}] = \frac{k(k-1)}{2k}\mathbb{E}[\zeta] = \frac{k-1}{2\lambda}. \end{aligned} \tag{6}$$

B. Service time

As stated earlier, the framing method implies that every packet includes $L(k) = kN + H$ bits. This means that the service time for a successful transmission of a packet to the destination is independent of the arrival process for input samples. However, the service time depends on the choice of k, the channel quality conditions, the channel transmission rate and the channel availability status.

We note that a packet transmission may be unsuccessful either due to channel errors or channel utilization request by high-priority primary nodes during the transmission session. Therefore, service time may involve multiple retransmissions. We first quantify the time required to transmit one copy of a packet denoted by S_1, which spans from the moment that a packet reaches the queue frontier until transmitting its very last bit. S_1 is a random variable which includes two parts i) the waiting time until the channel becomes accessible and the actual transmission time denoted by s_b.

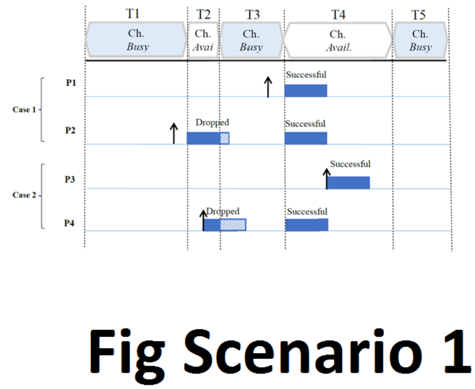


Fig. 3: Different scenarios for channel availability when a packet becomes ready for transmission.

If an uncoded system with rate R is assumed[1], the actual transmission time is $s_p = \frac{L}{R} = \frac{kN+H}{R}$, which is a deterinstic function of R and k.

However, the waiting time to have the channel accessible is a probabilistic value. In order to quantify this delay, we study two extreme *light* and *heavy* traffic regimes as follows.

*1) **Light traffic:*** In this regime, the rate of packet generation is low compared to the rate of successful packet transmission rate. Therefore, most packets meet an empty queue. Therefore, the state of the channel when met by a packet is totally independent of the previous packet. This implies that we can use a uniform distribution to represent the time epoch that a packet meets the shared channel.

Different scenarios for the channel state when a packet becomes ready for transmission is depicted in Fig.3. We have two major cases.
In case 1, the packet meets a *busy interval*, hence the transmission is postponed to the subsequent interval with available channel state. If the subsequent interval is long enough to carry out the transmission (e.g. $T_4 \geq s_b$ for packet P_1), the packet is transmitted successfully. Otherwise, retransmissions are attempted in the beginning of the subsequent *available intervals* until the packet transmission is accomplished (e.g. packet transmission of P_2 succeeds at the second attempt).

In case 2, the packets met *available intervals*, therefore the transmission is initiated immediately.Similar to case 1, If the current *available interval* is sufficient to accommodate a packet transmission, the packet is successfully transmitted without an interruption (e.g. packet P_3). On the other hand, if the current interval is too short, the packet

[1] In case of coded system, the equations require minor modifications. Lets posit the coding rate for information and header parts are R_D and R_H resulting in bit error probabilities of β_D and β_H, respectively. Then, the packet lengths are $L(k) = \frac{kN}{R_D} + \frac{H}{R_H}$ and the packet error probability is $\beta_P = 1-(1-\beta_D)^{\frac{kN}{R_D}}(1-\beta_H)^{\frac{H}{R_H}}$. The rest of derivations follows.

transmission is aborted and retransmissions are retried until an *available interval* is long enough to carry out the transmission (e.g. packet P_4 is transmitted in the second attempt at interval $T_4 \geq s_b$).

Now, we proceed with calculating the service for these two cases. Since the even and odd intervals are both exponentially distributed with means v and u, case 1 and 2 occur with probability $\frac{v}{u+v}$ and $\frac{u}{u+v}$, respectively. We denote the service time for case 1 and 2, by S_U and S_V, respectively. Therefore, the pdf of S_1 is a bimodal distribution with the following components:

$$f_{S_1}(s) = \frac{u}{u+v} f_{S_U}(s) + \frac{v}{u+v} f_{S_V}(s). \tag{7}$$

In order to calculate $f_{S_U}(s)$, we note that the service time for a packet with n retransmission is combination of four parts including: i) the remainder of the current busy interval denoted by Ω, ii) the summation of $n-1$ *available intervals* which are not sufficient for a single packet transmission denoted by $\sum_{i=1}^{n-1} T_{2i-1}$, iii) the summation of $n-1$ *busy intervals* before a successful transmission $\sum_{i=1}^{n-1} T_{2i}$ and iv) the actual transmission time s_b.

$$f_{S_U}(s) = \Omega + \sum_{i=1}^{n-1} T_{2i-1} + \sum_{i=1}^{n-1} T_{2i} + s_b. \tag{8}$$

Noting the memoryless property of exponential distribution for T_i, Ω_i can be considered as the right-hand side part of T_i if it is split by a uniformly distributed time epoch (i.e. $\Omega_i | T_i = t \ \sim \text{Uniform}(0, t)$). Hereafter, we omit the subscript for notation convenience.

Distribution of Ω is obtained by marginalizing out T as follows:

$$\begin{aligned} f_\Omega(\omega) &= \int_{t=0}^{\infty} f_{\Omega_i|T}(\omega|t) f_T(t) dt \\ &= \int_{t=0}^{\infty} \frac{U_\omega(t) - U_\omega(0)}{t} \frac{1}{u} e^{-t/u} dt \end{aligned} \tag{9}$$

The first and second order moments of Ω is simply obtained as

$$\begin{aligned} \mathbb{E}[\Omega] &= \int_{\omega=0}^{\omega=\infty} \omega f_\Omega(\omega) d\omega \\ &= \int_{\omega=0}^{\omega=\infty} \omega \int_{t=0}^{\infty} \frac{U_\omega(t) - U_\omega(0)}{t} \frac{1}{u} e^{-t/u} dt d\omega \\ &= \int_{t=0}^{\infty} \int_{\omega=0}^{\omega=t} \frac{\omega}{t} \frac{1}{u} e^{-t/u} d\omega dt = \int_{t=0}^{\infty} \frac{t}{2u} e^{-t/u} dt \\ &= u/2, \\ \mathbb{E}[\Omega^2] &= \int_{\omega=0}^{\omega=\infty} \omega^2 f_\Omega(\omega) d\omega \\ &= \int_{t=0}^{\infty} \int_{\omega=0}^{\omega=t} \frac{\omega^2}{t} \frac{1}{u} e^{-t/u} d\omega dt = \int_{t=0}^{\infty} \frac{t^2}{3u} e^{-t/u} dt \\ &= 2u^2/3, \\ &\Longrightarrow \sigma_\Omega^2 = \mathbb{E}[\Omega^2] - \left(\mathbb{E}[\Omega]\right)^2 = \frac{5u^2}{12}. \end{aligned} \tag{10}$$

The number of retransmission attempts n follows a geometric distribution with success parameter $p = P(T_{2i} \geq s_b = e^{-s_b/v})$.

Notations changes: using s_b for actual transmission time to avoid confusion with S_1, using n instead of k to count retransmissions, k is already used for the number of samples in a packet, avoid using new variables for intervals Au and Bu, ...

Revised until here.
The following text is not clear and needs to be clarified.

before calculating U it is necessary to define v' which is equal to average length of available time slots which has length smaller than service time and considered as insufficient time slot.

In order to calculate the second and third parts of(8) due to their dependency a good approach would be considering two adjacent time slots as one time slot then sum up k-1 of this bigger slot which is denoted by U, in these equations k is number of attempts that secondary nodes need to reach sufficient available time slot. k follows geometric distribution with success parameter of p. before calculating U it is necessary to define v' which is equal to average length of available time slots which has length smaller than service time and considered as insufficient time slot.

$$v' = \frac{-(sv1 + v)e^{-\frac{sv1}{v}}}{1 - e^{-\frac{sv1}{v}}} \tag{11}$$

$$\begin{aligned} \mathbb{E}[U] &= (\frac{1}{p} - 1)(u + v') \\ \mathbb{E}[U^2] &= (\frac{1}{p} - 1)(2u^2 + \frac{-(sv1^2 + 2vsv1 + 2v^2)e^{-\frac{sv1}{v}}}{1 - e^{-\frac{sv1}{v}}} + 2uv') \\ &+ (\frac{2-p}{p^2} + \frac{3}{p} + 2)(u + v')^2 \end{aligned} \tag{12}$$

Proof: See Appendix. ■

Combining (8), (10) and (21) results in the following Expected value for $S_1^{(\text{case 1})}$:

$$\begin{aligned} \mathbb{E}[S1^{(\text{case 1})}] &= sv1 + \frac{u}{2} + (\frac{1}{p} - 1)(u + v') \\ \mathbb{E}[(S1^{(\text{case 1})})^2] &= sv1^2 + 2\frac{u^2}{3} + (\frac{1}{p} - 1)(2u^2 \\ &+ \frac{-(sv1^2 + 2vsv1 + 2v^2)e^{-\frac{sv1}{v}}}{1 - e^{-\frac{sv1}{v}}} + 2uv') \\ &+ (\frac{2-p}{p^2} + \frac{3}{p} + 2)(u + v')^2] \\ &+ 2sv1(\frac{u}{2} + (\frac{1}{p} - 1)(u + v')) + \frac{2u}{2}(\frac{1}{p} - 1)(u + v') \end{aligned} \tag{13}$$

In order to calculate $f_{S_V}(s)$, Similar to $f_{S_U}(s)$ service time is combination of four parts plus one special case with probability p' which is for the case that subsequent interval is long enough for transmission (P_3):

$$f_{S_V}(s) = (1-p')(\Psi + \sum_{i=1}^{k-1} Av + \sum_{i=1}^{k} Bv + sv1) + (p')(sv1). \tag{14}$$

Therefor the first and second order moments of Ψ according to (10) is

$$\begin{aligned}
\mathbb{E}[\Psi] &= v'/2, \\
\mathbb{E}[\Psi^2] &= 2(v')^2/3, \\
&\implies \sigma_\Psi^2 = \frac{5(v')^2}{12}.
\end{aligned} \tag{15}$$

Similar to case 1 following equations can be derived:

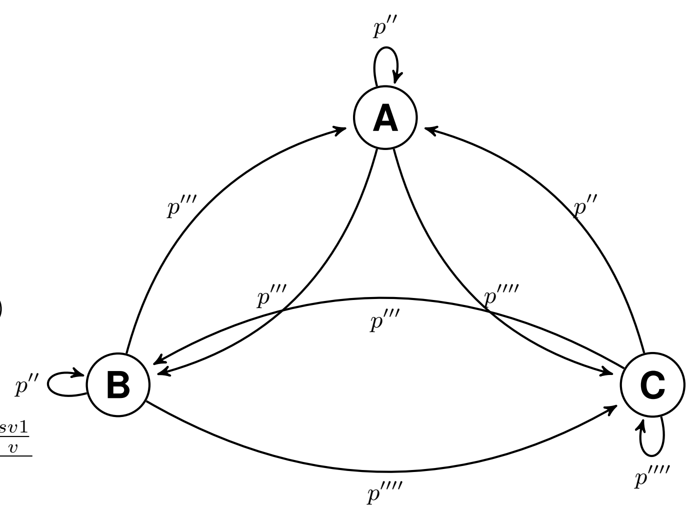
$$\begin{aligned}
\mathbb{E}[V] &= (\frac{1}{p}-1)(u+v')+u \\
\mathbb{E}[V^2] &= (\frac{1}{p}-1)(2u^2 + \frac{-(sv1^2+2vsv1+2v^2)e^{-\frac{sv1}{v}}}{1-e^{-\frac{sv1}{v}}} \\
&\quad + 2uv') + (\frac{2-p}{p^2} + \frac{3}{p} + 2)(u+v')^2 \\
&\quad + 2u^2 + 2u(\frac{1}{p}-1)(u+v')
\end{aligned} \tag{16}$$

$$\begin{aligned}
\mathbb{E}[S1^{(\text{case 2})}] &= (sv1 + (1-p\prime)(\frac{v'}{2} + (\frac{1}{p}-1)(u+v')+u) \\
\mathbb{E}[(S1^{(\text{case 2})})^2] &= sv1^2 + (1-p\prime)^2(\frac{2(v')^2}{3} \\
&\quad + (\frac{1}{p}-1)(2u^2 + \frac{-(sv1^2+2vsv1+2v^2)e^{-\frac{sv1}{v}}}{1-e^{-\frac{sv1}{v}}} \\
&\quad + 2\frac{v'}{2}((\frac{1}{p}-1)(u+v')+u) \\
&\quad + 2sv1(1-p)(\frac{(v')}{2}((\frac{1}{p}-1)(u+v')+u)
\end{aligned} \tag{17}$$

Combining (13) and (17) results in the following moments for S_1:

$$\begin{aligned}
\mathbb{E}[S1] &= \frac{u}{u+v}\mathbb{E}[S1^{(\text{case 1})}] + \frac{v}{u+v}\mathbb{E}[S1^{(\text{case 2})}] \\
&= \frac{u}{u+v}(sv1 + \frac{u}{2} + (\frac{1}{p}-1)(u+v')) \\
&\quad + \frac{v}{u+v}(sv1 + (1-p)(\frac{v'}{2} + (\frac{1}{p}-1)(u+v')+u) \\
\mathbb{E}[S1^2] &= \frac{u}{u+v}\mathbb{E}[(S1^{(\text{case 1})})^2] + \frac{v}{u+v}\mathbb{E}[(S1^{(\text{case 2})})^2] \\
&= \frac{u}{u+v}(sv1^2 + 2\frac{u^2}{3} + (\frac{1}{p}-1)(2u^2 \\
&\quad + \frac{-(sv1^2+2vsv1+2v^2)e^{-\frac{sv1}{v}}}{1-e^{-\frac{sv1}{v}}} + 2uv') \\
&\quad + (\frac{2-p}{p^2} + \frac{3}{p} + 2)(u+v')^2] \\
&\quad + 2sv1(\frac{u}{2} + (\frac{1}{p}-1)(u+v')) + \frac{u}{2}(\frac{1}{p}-1)(u+v')) \\
&\quad + \frac{v}{u+v}(sv^2 + (1-p)^2(\frac{2(v')^2}{3} \\
&\quad + (\frac{1}{p}-1)(2u^2 + \frac{-(sv1^2+2vsv1+2v^2)e^{-\frac{sv1}{v}}}{1-e^{-\frac{sv1}{v}}} \\
&\quad + 2\frac{v'}{2}((\frac{1}{p}-1)(u+v')+u) \\
&\quad + 2sv1(1-p)(\frac{(v')}{2}((\frac{1}{p}-1)(u+v')+u))
\end{aligned} \tag{18}$$

To calculate p' in (18) and find probability of each scenario in stationary state, The state diagram model which is depicted in[???] is used.



$$\begin{bmatrix} state_n A \\ state_n B \\ state_n C \end{bmatrix} = \begin{bmatrix} p'' & p'' & p'' \\ p''' & p''' & p''' \\ p'''' & p'''' & p'''' \end{bmatrix}^N \times \begin{bmatrix} state_0 A \\ state_0 B \\ state_0 C \end{bmatrix}$$

$stateA$ = sufficient available time slot
$stateB$ = Busy time slot
$stateC$ = insufficient available time slot
$p'' = \frac{v}{u+v} p(T \geq sv1) = \frac{v}{u+v}(e^{-sv1})$

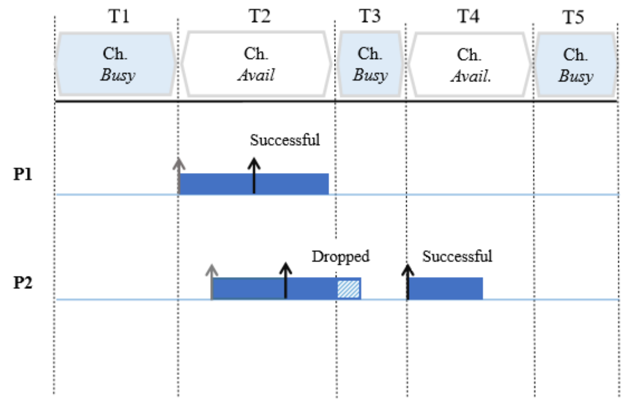


Fig. 4: Different scenarios for channel availability when a packet is ready for transmission.

$p''' = \frac{u}{u+v}$
$p'''' = \frac{v}{u+v} p(T < sv1) = \frac{v}{u+v}(1 - e^{-sv1})$

where $p\prime = p''$

2) Heavy traffic: In this regime there are two cases (Fig.4). In case 1, once the transmission is initiated, if the subsequent interval is long enough for complete transmission (e.g. P_1) the packet is successfully transmitted. Otherwise, the packet transmission is aborted as soon as the channel is seized by the primary nodes and the packet experiences even further delays until the channel becomes available for a sufficient duration to accomplish packet transmission (e.g. packet P_2).

Now, we proceed calculating the service for these two cases.

$$f_{S_1}(s) = (p_1) f_{P_1}(s) + (p_1) f_{P_1}(s). \tag{19}$$

In order to calculate $f_{P_2}(s)$, we note that service time is combination of four parts including the remainder of the current Available intervals denoted by Ψ and summation of possible intervals which are not sufficient for performing service which is denoted by $\sum_{i=1}^{k-1} Av$ and summation of possible intervals which primary nodes is occupied channel before scondary nodes reach sufficient available time slot which is denoted by $\sum_{i=1}^{k-1} Bv$ and finally time for single packet transmission sv_1.

$$f_{S_1}(s) = (p_2)(\Psi + \sum_{i=1}^{k-1} Av + \sum_{i=1}^{k} Bv) + sv1. \tag{20}$$

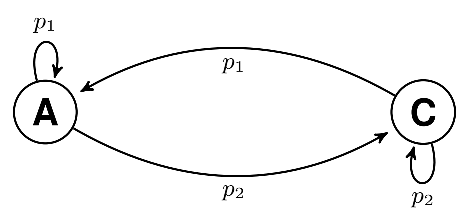
The first and second order moments of 20 is obtained based on (10)

$$\begin{aligned} \mathbb{E}[P_2] &= (\frac{1}{p} - 1)(u + v') \\ \mathbb{E}[P_2^2] &= (\frac{1}{p} - 1)(2u^2 + \frac{-(sv1^2 + 2vsv1 + 2v^2)e^{-\frac{sv1}{v}}}{1 - e^{-\frac{sv1}{v}}} + 2uv') \\ &+ (\frac{2-p}{p^2} + \frac{3}{p} + 2)(u + v')^2 \end{aligned} \tag{21}$$

And respectively:

$$\begin{aligned} \mathbb{E}[S1] &= (p_2)(\frac{1}{p} - 1)(u + v') + (p_1) sv1 \\ \mathbb{E}[S1^2] &= (p_2)^2((\frac{1}{p} - 1)(2u^2 + \frac{-(sv1^2 + 2vsv1 + 2v^2)e^{-\frac{sv1}{v}}}{1 - e^{-\frac{sv1}{v}}} + 2 \\ &+ (\frac{2-p}{p^2} + \frac{3}{p} + 2)(u + v')^2 \\ ) &+ (p_1)^2 sv1^2 \end{aligned} \tag{22}$$

To caclulate p_1 and p_2 the [???] is used which is converged to following model under heavy traffic regime:



$$\begin{bmatrix} state_n A \\ state_n C \end{bmatrix} = \begin{bmatrix} p_1 & p_1 \\ p_2 & p_2 \end{bmatrix} \times \begin{bmatrix} state_0 A \\ state_0 C \end{bmatrix}$$

$$state_0 A = p_1 = p(T \geq sv1) = (e^{-sv1})$$
$$state_0 C = p_2 = p(T < sv1) = (1 - e^{-sv1})$$

The equations in (18 and 22) correspond to the time required for transmitting a single copy of the packet, $S1$. Once the packet is received at the destination, its integrity is checked with an error checking mechanism (e.g. CRC codes). We assume zero error tolerance, meaning that a packet is considered in error even if a single bit is flipped due to channel errors, hence the packet error probability is $\beta_P = 1 - \alpha^{kN+H}$, where $\alpha = 1 - \beta$ is the successful bit transmission 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 $\alpha_P = 1 - \beta_P$:

$$\begin{aligned} \mathbb{P}r(R = n) &= (\beta_P)^{n-1}(1 - \beta_P) \\ &= \left[(1-\beta)\beta^{n-1}\right]^{kN+H}. \end{aligned} \tag{23}$$

The service time including potential re-transmission is:

$$S = \sum_{i=1}^{r} S_i \tag{24}$$

where S_i and r are independent and distributed according (19) and (23), respectively. Therefore, we have the following expressions for the moments of service time:

$$\begin{aligned}\mathbb{E}[S] &= \mathbb{E}_R\big[\mathbb{E}_{S|R}[S|R]\big] \\ &= \mathbb{E}_R\big[R\mathbb{E}_{S_i|R}[S_i|R]\big] = \mathbb{E}_R[R]\ \mathbb{E}_{S_i}[S_i] \\ &= \frac{1}{\alpha_P}\mathbb{E}[S1],\end{aligned} \tag{25}$$

$$\begin{aligned}\mathbb{E}[S^2] &= \mathbb{E}_R\big[\mathbb{E}_{S|R}[S^2|R]\big] \\ &= \mathbb{E}_R\big[\sum_{i=1}^{R}\mathbb{E}_{S_i}[S_i^2] + 2\sum_{i=1}^{R}\sum_{j=1,j\neq i}^{R}\mathbb{E}[S_i]\mathbb{E}[S_j]\big] \\ &= \mathbb{E}_R\big[R\mathbb{E}[S_i^2] + R(R-1)(\mathbb{E}[S_i])^2\big] \\ &= \mathbb{E}[R]\mathbb{E}[S_i^2] + \mathbb{E}[R(R-1)](\mathbb{E}[S_i])^2 \\ &= \frac{1}{\alpha_P}\mathbb{E}[S1^2]\end{aligned} \tag{26}$$

where we used pairwise independence of S_i as well as their independence from R. We substituted $\mathbb{E}[S_i]$ from (18).

The variance and coefficient of variation of service time, denoted by C_s, are obtained as follows:

$$\sigma_S^2 = \mathbb{E}[S^2] - \big(\mathbb{E}[S]\big)^2 \tag{27}$$

$$C_S^2 = \frac{\sigma_S^2}{\big(\mathbb{E}[S]\big)^2} = \frac{\mathbb{E}[S^2]}{\big(\mathbb{E}[S]\big)^2} - 1 \tag{28}$$

The obtained expressions for the service time moments are used in the subsequent overall delay analysis. The following are two important special cases:

C. Waiting time

So far, we quantified the delay corresponding to packet formation time as well as the time required for a successful transmission of a packet to the destination in light traffic and high traffic. Another source of delay is waiting time (w), which is the time each packet spends on the queuing system until the preceding packets have departed. The accurate waiting time calculations for GI/GI/1 queuing system is complex in general and involves obtaining the queuing transition kernel [20]. However, there are simplifying approximations under some mild conditions. One of the most popular approximations is the celebrated Kingman formula, which approximates the expected waiting time for a GI/GI/1 queuing system under heavy traffic regime provided that the service time and packet inter-arrival times are independent [21]. 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 Kingman equation as follows.

$$\mathbb{E}[W] \approx \frac{\rho}{(1-\rho)}\frac{\mathbb{E}[S](C_S^2 + C_\tau^2)}{2} \tag{29}$$

where ρ is the queue utilization factor defined as $\rho = \mathbb{E}[\mathbf{s}]/\mathbb{E}[\tau]$. Using equations (2) and (25), we have:

$$\rho = \mathbb{E}[S]/\mathbb{E}[\tau] = \frac{\lambda}{k\alpha_P}\big(\big(\frac{u}{u+v}(sv + \frac{u}{2} + (\frac{1}{p}-1)(u+v')\big) \tag{30}$$

$$+\frac{v}{u+v}(sv1 + (1-p)(\frac{v'}{2} + (\frac{1}{p}-1)(u+v') + u)\big)$$

D. End-to-end delay

The end-to-end delay D_j for a measurement sample X_j is defined as the time span from the sample generation epoch until its successful delivery to the target destination. For the utilized system model, if sample j is bundled into packet P_i, the end-to-end delay D_j consists of three terms including: i) packet formation delay averaged over all samples in packet i ($\bar{F}_i$), ii) waiting time for the corresponding packet in the queuing system (W_i) and iii) service time to transmit the packet to the destination including potential retransmissions (S_i). Thus, if k is selected as the framing parameter, the averaged end-to-end delay is defined as

$$D_j = \bar{F}_i + W_i + S_i, \quad \text{for } 1 + (i-1)k \le j \le ik \tag{31}$$

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

$$\begin{aligned}\mathbb{E}[D] &= \mathbb{E}[\bar{F}] + \mathbb{E}[W] + \mathbb{E}[S] \\ &\approx \frac{k-1}{2\lambda} + (\frac{\rho}{(1-\rho)}\frac{(C_S^2 + C_\tau^2)}{2} + 1)\mathbb{E}[S]\end{aligned} \tag{32}$$

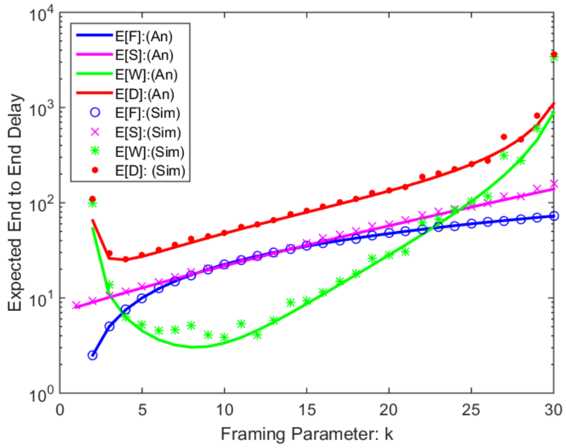
Moreover, due to the ergodicity of the queue, we can use the statistical average of the transmission delays obtained from simulations in section IV to compare with the analytically derived expressions for expected delay $\mathbb{E}[D]$ using the following relation:

$$\mathbb{E}[D] = \mathbb{E}[D_i] = \lim_{t\to\infty}\frac{1}{n(t)}\sum_{i=1}^{n(t)} D_i, \tag{33}$$

where $n(t) = \max\ \{i : t_i < t\}$ is the number of symbols arrived by time t.

E. Optimal Framing Interval

Equation in (32) 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 $s_1 = \frac{L}{R} = \frac{kN+H}{R}$ are functions of k. The rest of the parameters are either i) constant system setting (such as



(a)

Fig. 5: Comparison between the simulations and analytical derivations for different delay terms for the proposed framing policy under full channel access. Simulation parameters are $\lambda = 0.2$ sample/sec, $N = 8$ bit, $H = 128$ bit. (a): Uncoded system with $R = 100$ bits/sec, $\beta : 10^{-4}$.

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 (32) 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 properties. Minimizing equation (32) with respect to k can be easily solved using numerical methods or by extensive search.

IV. Simulation Results

In this section, we present the simulation results in order 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 of rate $\lambda = 0.1$. For any choice of framing parameter k, the number of samples is at least 10^4 or such that the number of packets is at least 10^3 , which ever is larger ($N_S = max(10^5, k \times 10^4)$. In order to obtain the statistical means of the waiting time, we take the average only over the 50% of the later packets in order to assure that the queue is stabilized and transition period is passed. For each scenario, we repeat the algorithm 4 times and take the average over multiple runs. We investigate both conventional (full channel access) and cognitive sensor scenarios with uncoded transmissions. The rest of parameters are set as $\lambda = 0.1$ samples/second, $N = 8$ bits, and $H = 64$ bits, unless specified otherwise.

In order to verify the accuracy of derived expressions for various delay terms under the developed framing and scheduling policies, we first investigate an uncoded system under full channel access ($u = 0, v \to \infty$). This condition reduces the cognitive sensor network to a conventional sensor network model.

TABLE I: Optimal framing parameter versus channel quality. Simulation parameters are $\lambda = 0.2$ sample/sec, $N = 8$ bit, $H = 128$ bit, $R = 100$.

Channel Error Prob. β	Optimal Framing Parameter: k
$\beta < 2 \times 10^{-3}$	1
$2 \times 10^{-3} \leq \beta < 6 \times 10^{-3}$	2
$6 \times 10^{-3} \leq \beta < 8 \times 10^{-3}$	3
$8 \times 10^{-3} \leq \beta < 1 \times 10^{-2}$	4
$1 \times 10^{-2} \leq \beta < 11 \times 10^{-2}$	5
$11 \times 10^{-2} \leq \beta < 12 \times 10^{-2}$	6
$12 \times 10^{-2} \leq \beta < 13 \times 10^{-2}$	6
$13 \times 10^{-2} \leq \beta$	-

Fig. 5 presents variations of different delay terms ($\bar{F}$, S, W and D) due to the choice of framing parameter k for uncoded communications. The averaged packet formation delay $\bar{F}$ (blue curve) is an increasing function of k, since the measurement samples wait for more subsequent samples to form a single packet. Likewise, the expected inter-packet arrival time $\mathbb{E}[\tau]$ increases with k. Similarly, increasing k results in a 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 main parts, a constant time to transmit H header bits regardless of the choice of k, and a variable part to transmit kN information bits. Therefore, 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 confirm the analytical derivation for both coded and uncoded systems. The minor mismatch for waiting time corresponds to the well-known approximation in Kingman formula. However, the impact of this approximation on the end-to-end delay is negligible.

Impact of channel quality on the end-to-end delay is demonstrated in Fig. 6. The channel quality is represented with bit error probability β. As β increases, the packet drop rate and re-transmission rate increase accordingly, which in turn causes a shift in the expected end-to-end delay. This effect is higher for larger k values for zero error tolerance system (Fig., 6a). 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 Fig. 6b, with threshold values in Table. I. For instance, for an uncoded system with parameters ($\lambda = 0.1$, $N = 8$, $H = 64$ bit, $R = 20$), if the channel error rate is 4×10^{-3}, the optimal framing policy is combining each $k = 7$ consecutive samples into a single transmission packet.

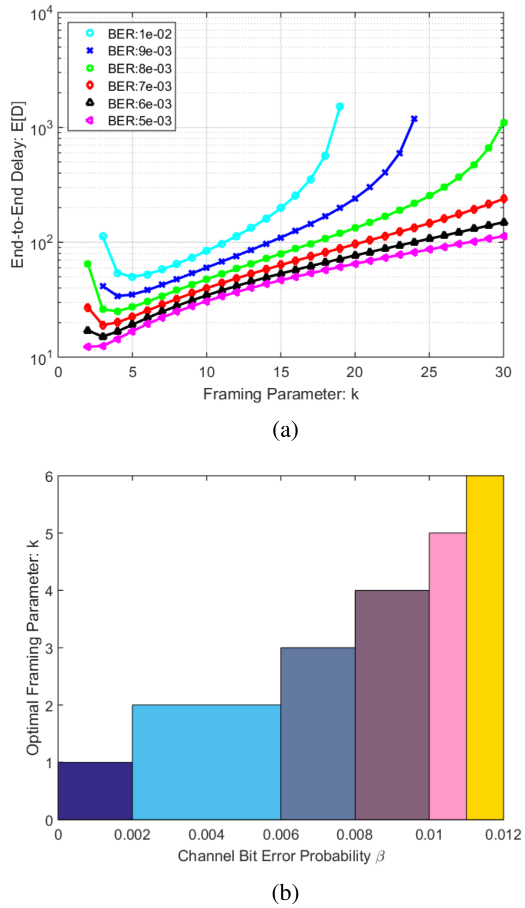


Fig. 6: Impact of the channel quality on the optimal framing policy. (a): End-to-end delay $\mathbb{E}[D]$ is plotted versus framing parameter k for different channel error probabilities β. (b): Optimal framing parameter k for different channel quality regions. Simulation parameters are $\lambda = 0.2$ sample/sec, $N = 8$ bit, $H = 128$ bit, $R = 100$.

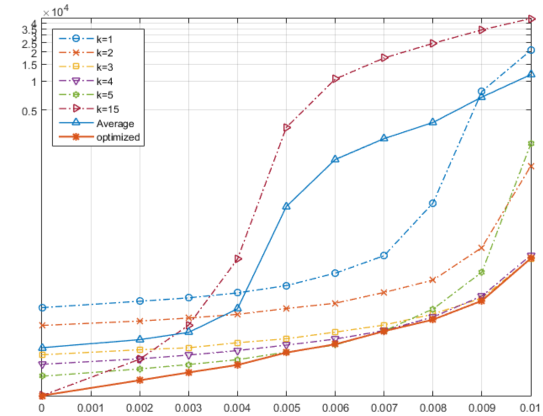


Fig. 7: Compare influence of proposed packet length on end to end delay in different Channel quality Simulation parameters are $\lambda = 0.2$ sample/sec, $N = 8$ bit, $H = 128$ bit, $R = 100$.

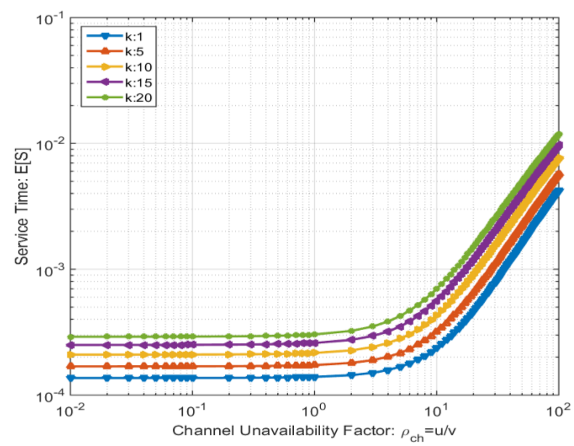


Fig. 8: Service time $\mathbb{E}[S]$ is plotted versus framing parameter k for different channel unavailability factor $\rho_{ch} = \frac{u}{u+v}$. Simulation parameters are $\lambda = 30$ sample/sec, $N = 8$ bit, $H = 64$ bit, $\beta_D = \beta_H = 10^{-6}$, $R_D = R_H = \frac{1}{2}$, $R = 10^6$.

Fig. 8 presents the behavior of expected service time $\mathbb{E}[S]$ with varying channel unavailability factor $\rho_{ch} = \frac{u}{v}$ for cognitive sensors 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 $\mathbb{E}[S]$ is proportional to ρ_{ch} as shown in Fig. 8.

V. 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 available channel sate. 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, 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 cause the queuing system to become 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.

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