Maximizing Energy Efficiency of Cognitive Wireless Sensor Networks with Constrained Age of Information

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***Abstract*—A cognitive wireless sensor network is considered, where a cluster of secondary sensors utilize channel vacancies of a primary network and transmit their measurement samples to a common sink node. We propose a joint framing and scheduling policy that optimizes energy efficiency of communication system under strict constraints on the expected *age of information*. The age of information is defined as the timespan from the sampling epoch to the successful delivery of the samples to the sink node including framing time, queuing time, waiting time for channel vacancies and transmission time.**

Firstly, we develop a number-based framing policy to determine the number of samples bundled into data packets with constant header sizes. Then, we quantify the impact of this policy on the age of information and communication energy efficiency by characterizing the utilized queuing dynamics, packet discard rate and retransmission probability. The derived closed-form expressions for the age of information and energy efficiency are used to regularize packet lengths based on the current sampling rate, channel quality and channel utilization rate by primary users. The proposed method can be used to develop low-cost and energy-efficient network of unlicensed sensors for delay sensitive applications such as body area sensor networks.

***Index Terms*—Cognitive Sensor Networks, Energy Efficient Communication, Age of Information, Queuing Dynamics, Network Optimization.**

I. INTRODUCTION

Green wireless communication has recently gained an unprecedented attention [1]. The key goal of green communication is to minimize the environmental impacts of communication systems by improving their energy efficiency and consuming less sources [2]–[4]. In this work, we propose a transmission method with maximal energy efficiency for cognitive sensor networks, where unlicensed sensor nodes, considered as Secondary Nodes (SUs), monitor channel utilization by Primary Users (PUs) and transmit their collected data packets in channel vacancies. The proposed energy efficient communication method prolongs the battery lifetime of sensors, hence is well suited to implement low-cost sensor networks for applications with constant data aggregation requirements and strict constraints on the *age of collected information* such as body area sensor networks [5]–[7].

Here, we use Cognitive Radio Networking (CRN), which has recently emerged as a promising substitute for conventional spectrum allocation methods due to facilitating free spectrum access for unlicensed SUs without causing interference to PUs [8], [9].

CRN implementation includes three main categories including *underlay*, *overlay* and *interweave* [10]. In the *underlay* implementation, SUs share the channel with PUs, while avoiding harmful interference to PUs by limiting their transmit power and using techniques such as spread spectrum and beamforming. In *overlay* implementation, information about the transmission method and channel utilization is provided by PUs and therefore SUs are able to avoid simultaneous transmissions. In *interweave* method, SUs monitor the channel and seize the channel only if it is not utilized by PUs. In this work, we choose the latest method (*interweave*) to implement an efficient and low-cost transmission setup for Cognitive Wireless Sensor Networks (CWSNs), since it is interference-free and does not require coordination with the primary network.

Another key performance indicator of sensing applications is the *age of information*, which is defined as the timespan from the sampling epoch until the information is successfully delivered to the intended destination for further processing. This parameters comprises packet formation and the end to end transmission delay [11]. There has been a recent continued interest in minimization the age of information in sensor networks, especially for delay sensitive applications [12]–[18]. This optimization is even more critical for cognitive sensor networks with sporadic channel access, where SUs experience longer delays due to intermittent channel availability and frequent transmission interruptions by licensed users [19]–[21].

In this paper, we propose a number-based framing policy for a cluster of sensors in order to find an optimal way of bundling their measurement samples into transmit packets such that energy consumption per measurement sample is minimized while ensuring that the expected age of information remains below a certain limit. In order to avoid channel access collisions among sensors within the CWSN, we use polling method, but other coordinated channel access methods (e.g. reservation-based and token based methods) or random access methods (e.g. Aloha) are also applicable. The key idea is to characterize the impact of packet lengths on the energy efficiency and age of information by investigating the queue dynamics of the SUs under partial channel availability and transmission interruptions by PUs.

A. Related works

The proposed methodology builds upon two lines of research including i) analysis of queue dynamics in cognitive networks and ii) assessing the impact of packet lengths on transmission performance metrics. The following is a brief review of the related works in both directions.

*1) **Queue dynamics of cognitive wireless sensor networks**:* Queuing system of CWSNs can be considered as a special case of conventional queuing systems, where each serving period is subject to potential initiation delays (to wait for channel vacancies) and possible interruptions (due to PUs' transmissions). More specifically, SU's queue in an interweaved CWSN can be modeled as a Preemptive Priority Queue (PPQ), where users are assigned with different priority classes. In this approach, upon arrival of a High Priority (HP) user, the server starts serving the HP immediately, no matter if the server is in the idle mode or is serving a Low Priority (LP) user. Therefore, LP services are subject to potential interruptions. This queuing system is well studied in the literature. The following are a number of examples: In [22], the authors proposed a PPQ model with a retrial policy. If a LP's service is interrupted, the LP is directed to a retrial queue and waits until the server becomes available. A newly arrived HP or LP user competes with the LP user at the head of the retrial queue. The stability conditions and the steady state performance of this queuing system are studied. However, the introduced retrial policy is not applicable to our proposed CWSN. Firstly, in their model an interrupted packet for a LP user is not discarded rather it continues to complete its remaining service, while we follow the more realistic approach in packet based networks by discarding the interrupted packet and retransmitting it when the channel becomes available. Furthermore, their model is in contradiction with the First Come First Serve (FCFS) discipline, since the newly arrived user competes with the user in the front of the retrial queue. In [23], two priority classes are considered for queued users and the queuing delay is characterized using a discrete-time model. In this article, the arrival processes for the two classes of users are assumed to be correlated, which violates the assumption of independent arrival processes for PUs and SUs in CWSNs.

Some recent articles more specifically used PPQ modeling to analyze communication systems in cognitive networks. For instance, in [24], an analytical framework is proposed to analyze a M/G/1 queue with an arbitrary service time distribution and PPQ discipline. In [25], the authors proposed a channel reservation method using PPQ model to prioritize between the interrupted SUs and the new session requests by the SUs to increase the queue's stability and reduce the number of unnecessary retransmissions. In [26], a close form expression is derived for the average service time for multiple traffic classes with different levels of service priorities. In [27], an exact probability distribution function is found for SU's end-to-end delivery time considering Poisson distribution for the packet arrival and assuming exponential distribution for the consecutive *busy* and *idle* channel intervals. All of the aforementioned models in [24]–[27] consider a restrictive assumption of memoryless packet arrival process. Thereby, these models are not applicable to our proposed system model, where the packet interarrival is not memoryless.

*2) **Optimizing transmission efficiency through packet size adaptation**:* Several methods are proposed in the literature to optimize communication systems transmission energy efficiency of cognitive users. These methods mainly focused on two aspects including i) optimizing spectrum sensing to alleviate the impact of interference on energy consumption of SUs [28], [29] and ii) improving energy efficiency by optimizing various system parameters such as the number of active SUs, SU's data rates, the number of shared channels and packet size [30]–[32].

In this work, we exploit the variability of packet sizes in contemporary communication protocols to maximize energy efficiency while maintaining the age of information below a predefined limit. A few research works have been focused on regularizing packet lengths to optimize the communication performance for a single wireless system. For instance, the idea of local packet length adaptation to maximize the system overall throughput in WLAN channels is introduced in [32]. However, to the best of our knowledge, the impact of packet lengths on the key transmission performance indicators are not well understood for queued cognitive sensor networks, when the shared channel is partially available to SUs and are subject to frequent interruptions. The following is a short list of more relevant recent works:

In [33], the optimal packet size for a transmission system through shared fading channels is studied for SUs. The author found an optimal packet size, which maximizes throughput while maintaining the interference probability below a certain threshold. The optimal packet size for SUs is derived in [34], which minimizes power consumption while ensuring an acceptable interference level. In summary, the above mentioned works either investigated the queuing dynamic of CRN or aimed at adjusting packet sizes to optimize a desired system performance indicator. In this work, we try to bridge these lines of researches and make an optimal policy to regularize packet lengths for SUs by considering the queuing dynamics with memoryless interarrival distributions.

B. Contributions

A joint framing and scheduling policy for CWSN for interweave based implementation with FCFS discipline is investigated. Most previously reported studies implement and optimize transmission systems for a given packet generation process. Here, we regulate the packet arrival process by controlling the number of symbols that form data packets. The resulting packet interarrival is Gamma distributed, hence not memoryless anymore. A concrete formulation is provided to study the *age of information* and transmission energy efficiency for cognitive sensors with queued transmission and opportunistic channel access under *light* and *heavy* traffic regimes. This characterization enables us to optimize either one of *age of information* and transmission energy efficiency as desired objectives, or to optimize one objective when the other one is constrained. We choose to optimize the energy efficiency if the expected age of information is constrained, since it is a more realistic objective in time-sensitive sensor networks. The proposed methodology is general and applicable to a wide variety of queued cognitive transmissions with non-memoryless input traffic process and partial channel access. This model paves the road for implementing a new class of low-complexity, delay sensitive and energy efficient cognitive sensor networks.

The rest of this paper is organized as follows. In section II, the system model and the proposed framing policy is presented. In section III, the problem of maximizing energy efficiency for the proposed system model is formulated. The age of information is characterized in section IV. The simulation results are provided in section V, followed by concluding remarks in section VI.

II. System Model

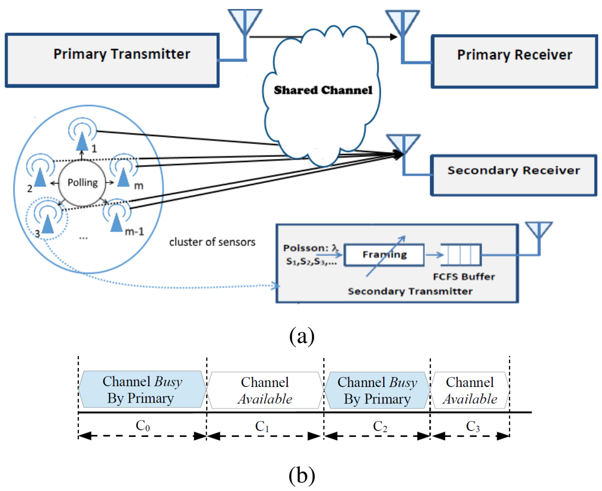


Fig. 1: System model: (a) A cluster of cognitive sensors share channel with a primary transmitter-receiver pair. Each sensor collects measurement samples, combines them into packets with constant header sizes, buffers them in a FCFS queue for opportunistic transmission through the shared channel. Polling method is used to coordinate secondary sensors access to channel vacancies. (b) The time axis is split into intervals with alternating *busy* and *available* channel states from the secondary users perspective.

The system model includes the coexisting primary and secondary networks sharing the same channel of rate R_{ch}, as depicted in Fig. 1. A primary network is the owner of the bandwidth and consists of transmitter-receiver pairs, while the secondary network includes a cluster of m unlicensed sensors directly communicating to a data fusion center. We follow the interweave-based cognition approach with a perfect Channel State Information (CSI) assumption, such that the PUs access the channel to send their packets regardless of the presence of secondary nodes and the SUs monitor the channel continuously and transmit theirs packets in channel vacancies. The SUs discard their current packet and release the channel as soon as a PU seizes the channel. Therefore, the SUs are totally absent from the PUs' perspective. We use automatic repeat request (ARQ) retransmission mechanism. If a secondary node's transmission is interrupted due to a PU's channel request or if the received packet is erroneous due to channel errors, the packet is discarded and the sensor node retries transmitting the packet until an error-free copy is delivered to the intended destination.

The secondary network employs polling method (as developed in IEEE 802.11 and 802.12 standard series) to coordinate channel access among the sensors to avoid inter-sensor collisions. If the shared channel becomes available to the secondary network, the senors transmit their packets (if any) in a cyclic sequential order ($1 \to 2 \to ... \to m-1 \to m \to 1 \to 2 \to ...$). In the next channel vacancy, the lastly interrupted sensor transmits its packet. We also study random access methods (e.g. Aloha), which is more desired in *light* traffic conditions. For the sake of brevity, we first analyze a secondary system with only one sensor and then highlight the changes involved in the analysis to extend the results to a case of using multiple sensors.

A. Framing method

A sequence of N-bit measurement samples $\{X_i\}_{i=0}^{\infty}$ is generated according to a Poisson process with rate λ. Therefore, the sample interarrival times, denoted by ζ_j are independent and exponentially distributed random variable with mean $1/\lambda$. Each measurement sample is quantized and digitized to an N-bit value. Under the developed *Number-based framing policy*, each sensor encapsulates k consecutive samples $\{X_{k(i-1)+1}, X_{k(i-1)+2}, \dots, X_{ki}\}$ into a single packet P_i as shown in Fig. 2. For a constant header size of H, the length of packets is $l(k) = kN + H$.

In order to fully determine the packet arrival process, we also need to obtain the distribution of the packet interarrival times denoted by τ_i. We note that the packet interarrival time is the summation of k consecutive sample interarrival times (i.e. $\tau_i = T_i - T_{i-1} = \sum_{j=1}^{k} \zeta_{i_j}, \zeta_j \sim \exp(\zeta; 1/\lambda)$). The Moment Generating Function (MGF) for an exponentially distributed random variable ζ is $M_\zeta(t) = \mathbb{E}[e^{t\zeta}] = \frac{\lambda}{\lambda - t}$. Thus, the MGF of τ_i is $M_{\tau_i}(t) = \mathbb{E}[e^{t\tau_i}] = \prod_{j=1}^{k} M_{\zeta_j}(t) = \big(M_\zeta(t)\big)^k = \big(\frac{\lambda}{\lambda - t}\big)^k$, 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:

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

These parameters are used in calculating the waiting time in section IV-C.

B. Licensed channel dynamic model

Here, we assume that the channel access process by the PUs follows a Poisson process. In other words, the channel in

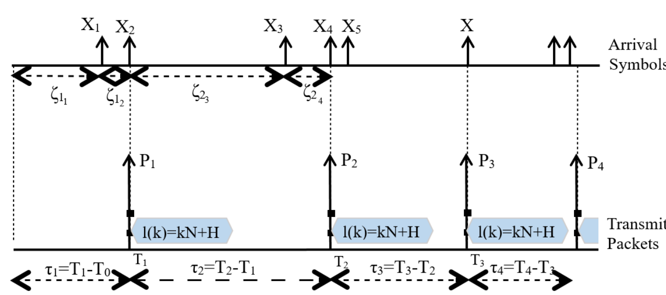


Fig. 2: Number-based *framing policy*: Sensor measurements $\{X_j\}_{j=1}^{\infty}$ are generated according to a Poisson process with rate λ. The sample interarrival times ζ_j are exponentially distributed with mean $1/\lambda$. Each k consecutive samples $\{X_{k(i-1)+1}, X_{k(i-1)+2}, \dots, X_{ki}\}$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

time domain is split into consecutive intervals denoted by C_i ($i = 0, 1, 2, \dots$), with alternating *available* and *busy* states. The odd and even intervals are exponentially distributed with different mean values of v and u, respectively, as follows:

$$f_{C_i}(c) = \begin{cases} \exp(c; u) = \frac{1}{u} e^{-c/u} & i = 0, 2, 4, \dots, \\ \exp(c; v) = \frac{1}{v} e^{-c/v} & i = 1, 3, 5, \dots. \end{cases} \quad (3)$$

The assumption of exponential distributed channel access process is a commonly accepted assumption in communication systems. Its memory-less property as

$$\mathbb{P}r(C_i > t + \alpha | C_i > \alpha) = \mathbb{P}r(C_i > t) = e^{-t/v}, \quad \text{for } i = 1, 3, 5, \dots \; . \quad (4)$$

means that the probability of continuation of the channel availability for additional t seconds is independent of its history. An immediate consequence of this property is that the SU starts transmitting its packet if the channel is available no matter how long passed since the last channel utilization by the PUs.

III. Problem formulation

In this work, we follow the popular definition of Energy Efficiency (EE), which is defined as the average number of successfully transmitted bits per unit energy consumption as follows:

$$\text{EE} = \quad (5)$$

$$\frac{\text{number of transmitted information bits/packet}}{\text{expected power consumption/packet}}. \quad (6)$$

where the approximation is due to taking expect value. This quantity varies over time and is a function of the channel bit error rate and the average channel availability rate. In order to calculate the total energy in (5), we note that the total power consumption of SU includes two parts, P_p and P_b. P_p is the power consumption which is used once per packet for taking measurements, queuing, channel selection, and spectrum handoff [30]. On the other hand, P_b is the power required for actual transmission of one bit including potential retransmission. Consequently, EE can be written as:

$$EE(k) = \frac{kN}{P_b(\mathbb{E}[R_d l_{discard}(k)] + l(k))\mathbb{E}[R] + P_p} \quad (7)$$

The equation (6) provides an explicit relation between the framing parameter k and the energy efficiency. Here, R_d is the number of retransmission caused by PUs when they start seizing the channel. $l_{discard}(k)$ is the average number of bits that are sent in an unsuccessful transmission attempt before a PU seizes the channel. R is the number of retransmissions because packets arrive at the destination with error and $l(k)$ is the number of bits for a complete packet. Therefore, $\mathbb{E}[R_d l_{discard}(k)] + l(k))\mathbb{E}[R]$ is the average number of transmitted bits per packet. In order to optimize EE when the *age of information* is constrained, we need to solve the following optimization problem:

$$\begin{cases} k* & = \underset{k}{\text{argmin}}\{1/EE(k)\} \\ \text{s.t.} & \mathbb{E}\{D(k)\} < D_0, \end{cases} \quad (8)$$

where $D(k)$ is the age of information characterized in section IV and D_0 is a desired threshold based on the tolerable delay in collecting information for the desired application.

IV. The age of information

In order to characterize the age of information, we quantify different delay terms as follows.

A. Packet formation time

The first delay source is the timespan from the measurement epoch until the corresponding packet is formed. According to the framing method described in section II-A (Fig. 2), the interarrival time between samples $j-1$ and j is ζ_j, therefore a sample X_j, $(i-1)k + 1 \leq j \leq ik$ 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

$$\bar{F}_i = \frac{1}{k} \sum_{j=(i-1)k+1}^{ik} \left(\sum_{l=j+1}^{ik} \zeta_l \right). \quad (9)$$

We obtain the following expected value for the averaged packet formation delay:

$$\begin{aligned} \mathbb{E}[F] = \mathbb{E}[\bar{F}_i] &= \frac{1}{k} \mathbb{E}\Big[\sum_{j=1}^{k} (k-j) \zeta_{(i-1)k+j} \Big] \\ &= \frac{1}{k} \Big[\sum_{j=1}^{k} (k-j) \mathbb{E}[\zeta_{(i-1)k+j}] \Big] \\ &= \frac{k(k-1)}{2k} \mathbb{E}[\zeta] = \frac{k-1}{2\lambda}. \end{aligned} \quad (10)$$

B. Service time

Based on the framing method, each packet includes $l(k) = kN + H$ bits, which implies that the service time for a successful packet transmission is independent of the sample arrival process. However, the service time depends on the choice of k, the channel error probability β, the channel transmission rate R_{ch} and the channel availability parameters u, v. Different scenarios arise for the channel state, when a packet in the frontier of the transmit queue becomes ready for transmission, as depicted in Fig.3. The scenarios include two major cases.

In case 1, the packet meets an *available* interval, thus the transmission is initiated immediately. If the remaining of the current *available* is sufficient to accommodate a packet transmission, the packet is transmitted without an interruption (e.g. packet P_1). On the other hand, if the current interval is not long enough, the packet transmission is aborted and retransmissions are attempted at the subsequent *available* intervals until transmission is accomplished (e.g. packet P_2).

In case 2, the packet meets a *busy* interval, hence the transmission is postponed to the next *available* interval. If

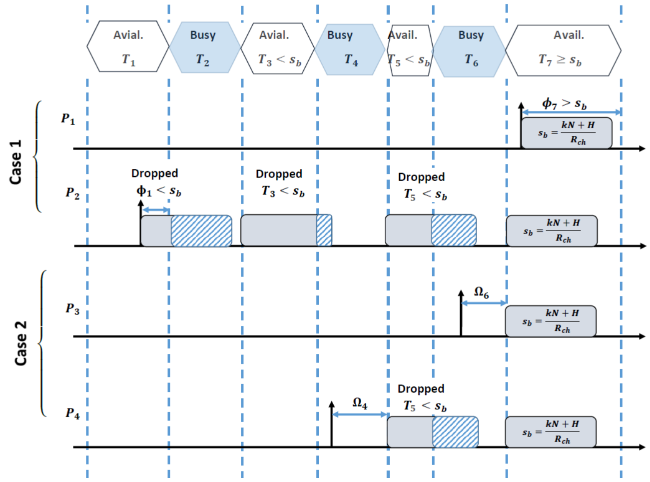
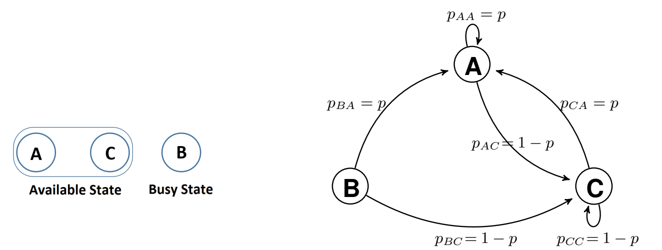


Fig. 3: Different scenarios for channel availability when a packet becomes ready for transmission. Case 1 and 2, respectively, represents scenarios that the packet meets *available* and *busy* intervals.

the subsequent interval is long enough to carry out the transmission, the packet is transmitted successfully (e.g. packet P_3). Otherwise, the current copy of packet is discarded and retransmissions are performed in the subsequent *available* intervals until the packet transmission is completed (e.g. packet P_4).

We note that a packet transmission may fail either due to channel errors or a sudden channel request by PUs 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. Then, we consider the impact of retransmissions. To characterize service time and waiting time, we first define the following terms, which are used in the subsequent analysis.

- **State**: The status of the channel when the SU attempts to transmit a packet.
- **State A**: The SU sends its data packet through the channel in an *available* interval and the channel remains available (i.e. is not requested by the PU) until the completion of the current packet transmission.
- **State B**: The SU's packet becomes ready for transmission while the channel is *busy*, therefore the SU waits until the channel becomes available.
- **State C**: The channel is primarily in an *available* state, hence the SU sends its packet. However, the PU seizes the channel during the SU's transmission session. The SU aborts the current transmission and waits until the next channel vacancy to send its packet.
- **Heavy traffic**: This scenario refers to the case, where the probability of meeting an empty queue diminishes. Here, we use the *saturated traffic* approximation, which implies that meeting an empty queue occurs with probability 0. In other words, w_n in Lindley's equation ($w_{n+1} = (w_n + S - \tau_n)^+$) [35] is greater than zero with probability 1.
- **Light traffic**: In this scenario, the probability of facing nonempty queue is close to 0. Hence, a packet starts service as soon as it is formed. In the other word, w_n in Lindley's equation is zero with probability close to 1.



(a): light traffic (b): heavy traffic

Fig. 4: State diagram for (a) *light* and (b) *heavy* traffic regimes as defined in section IV-B. (a): In *light* traffic mode, a packet in frontier of the queue meets the channel in one of the three states regardless of the state of the preceding packet. In this case, state A, B, and C occur with probabilities $\frac{v}{u+v}e^{-s_b/v}$, $\frac{u}{u+v}$, and $\frac{v}{u+v}(1-e^{-s_b/v})$, respectively. (b): In *heavy* traffic mode, each packet meets the channel right after the departure of the preceding packet, hence all packets meet the channel in *available* status (state A or C). However, the probability of landing at states A and C is independent of the previous packet and is equal to $p = e^{-s_b/v}$ and $1-p$, respectively.

Fig. 4 shows state transition diagram for both traffic modes. Before, proceeding with the details of analysis for both modes, we note that if one may find the exact transition kernel for the queue, then he can find the probability of facing an empty queue α_e. Then, the state diagrams for both traffic modes can be integrated into one state transition diagram with transition probabilities $P_{ij} = \alpha_e P_{ij}$ [in *light* traffic mode] $+(1-\alpha_e)P_{ij}$ [in *heavy* traffic mode]. However, finding the exact queue transition kernel and hence finding α_e is not analytically tractable. Now, we proceed with detailed derivations for both *light* and *heavy* traffic regimes as follows.

1) Light traffic regime: In this regime, the rate of packet generation is much lower than the rate of successful packet transmission rate and the performance of the system approaches a queue-less system. An immediate consequence is that a packet's departure time is independent of the preceding packet, which implies independent channel states when met by two consecutive packets. In other words, the three states A, B and C for each packet occurs independent of the state of the preceding packet, as depicted in Fig. 4 (a). Therefore, we can assume a uniform distribution for the time epoch, at which the packet meets the channel.

Based on this assumption, we proceed with calculating the service time for this scenario by investigating case 1 and 2 defined in section IV-B. Since the odd and even intervals are both exponentially distributed with means v and u, case 1 and 2 occur with probabilities $\frac{v}{u+v}$ and $\frac{u}{u+v}$, respectively. We denote the service time for case 1 and 2, by S_V and S_U, respectively. Therefore, the probability density function of S_1 is a bimodal distribution as follows:

$$f_{S_1}(s) = \frac{u}{u+v} f_{S_U}(s) + \frac{v}{u+v} f_{S_V}(s). \quad (11)$$

In order to calculate $f_{S_U}(s)$, we note that the service time for a packet with n transmissions attempts is combination of four terms including i) the remainder of the current *busy* interval denoted by Ω_j, ii) the summation of $n-1$ subsequent *available* intervals with $T \leq s_b$, which are not sufficient for a single packet transmission: $\sum_{i=1}^{n-1} T_{j+2i}$, iii) the summation of $n-1$ *busy* intervals before a successful transmission: $\sum_{i=1}^{n-1} T_{j+2i-1}$, and iv) the actual transmission time s_b. The scenario P_4 in Fig. 3, represents this case for $j=4$ and $n=2$.

$$S_U = \Omega_j + \underbrace{\sum_{i=1}^{n-1} T_{j+2i-1} + \sum_{i=1}^{n-1} T_{j+2i}}_{A} + s_b. \tag{12}$$

Noting the memory-less property of exponential distribution for T_j, Ω_j can be considered as the right-hand side part of T_j if it is split by a uniformly distributed time epoch (i.e. $\Omega_j | T_j = t \sim \text{Uniform}(0,t)$). Hereafter, we set $j=0$ and omit unnecessary subscripts for notation convenience. Distribution of Ω is obtained by marginalizing out T as follows:

$$\begin{aligned} f_\Omega(\omega) &= \int_{t=0}^{\infty} f_{\Omega_i|T}(\omega|t) f_T(t) dt \\ &= \int_{t=0}^{\infty} \frac{U_\omega(t) - U_\omega(0)}{t} \frac{1}{u} e^{-t/u} dt \end{aligned} \tag{13}$$

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

$$\begin{aligned} \mathbb{E}[\Omega] &= \int_{\omega=0}^{\omega=\infty} \omega f_\Omega(\omega) d\omega \\ &= \int_{\omega=0}^{\omega=\infty} \omega \int_{t=0}^{\infty} \frac{U_\omega(t) - U_\omega(0)}{t} \frac{1}{u} e^{-t/u} dt d\omega \\ &= \int_{t=0}^{\infty} \int_{\omega=0}^{\omega=t} \frac{\omega}{t} \frac{1}{u} e^{-t/u} d\omega dt \\ &= \int_{t=0}^{\infty} \frac{t}{2u} e^{-t/u} dt = u/2, \\ \mathbb{E}[\Omega^2] &= \int_{\omega=0}^{\omega=\infty} \omega^2 f_\Omega(\omega) d\omega \\ &= \int_{t=0}^{\infty} \int_{\omega=0}^{\omega=t} \frac{\omega^2}{t} \frac{1}{u} e^{-t/u} d\omega dt \\ &= \int_{t=0}^{\infty} \frac{t^2}{3u} e^{-t/u} dt = 2u^2/3, \\ &\Longrightarrow \sigma_\Omega^2 = \mathbb{E}[\Omega^2] - \big(\mathbb{E}[\Omega]\big)^2 = 5u^2/12. \end{aligned} \tag{14}$$

The number of retransmission attempts n follows a Geometric distribution with success parameter $p = P(T_{j+2i-1} \geq s_b) = e^{-s_b/v}$. In order to calculate the second and third parts of (11), one simplifying approach would be to combine two adjacent time slots (T_{2i-1} and T_{2i}) into one time slot whose length is exponentially distributed with mean $u+v$ as follows:

$$A = \sum_{i=1}^{n-1} T_{2i-1} + \sum_{i=1}^{n-1} T_{2i} = \sum_{i=1}^{n-1} (T_{2i-1} + T_{2i}). \tag{15}$$

The first and second order moments of the expression in (14) is obtained as follows:

$$\begin{aligned} \mathbb{E}[A] &= \mathbb{E}[\sum_{i=1}^{n-1} (T_{2i-1} + T_{2i})] \\ &= \mathbb{E}[n] \mathbb{E}[T_{2i-1} + T_{2i}] \\ &= (1/p - 1)(u + v_e), \\ \mathbb{E}[A^2] &= \mathbb{E}[\big(\sum_{i=1}^{n-1} (T_{2i-1} + T_{2i})\big)^2] \\ &= (1/p - 1)(2u^2 \\ &+ \frac{-(s_b^2 + 2vs_b + 2v^2) e^{-s_b/v}}{1 - e^{-s_b/v}} + 2uv_e) \\ &+ (\frac{2-p}{p^2} + \frac{3}{p} + 2)(u + v_e)^2, \end{aligned} \tag{16}$$

where

$$\begin{aligned} v_e &= \mathbb{E}[T_{2i} | T_{2i} < s_b] & (17) \\ &= \int_{t=-\infty}^{s_b} t f_{T_{2i}}(t | T_{2i} < s_b) dt \\ &= \frac{\int_{t=0}^{s_b} t f_{T_{2i}}(t) dt}{F_{T_{2i}}(s_b)} \\ &= \frac{1 - (s_b v + 1) e^{-s_b/v}}{(1 - e^{-s_b/v}) v}. & (18) \end{aligned}$$

is the mean of *available* intervals with lengths less than s_b.

Combining (11), (13) and (15) provides the following first and second order moments for S_U:

$$\begin{aligned} \mathbb{E}[S_U] &= s_b + \frac{u}{2} + \mathbb{E}[A], \\ \mathbb{E}[(S_U)^2] &= s_b^2 + 2\frac{u^2}{3} + \mathbb{E}[A^2] \\ &+ s_b u + (2s_b + u)\mathbb{E}[A]. \end{aligned} \tag{19}$$

A similar approach can be used to obtain the moments of $f_{S_V}(s)$, when the packet meets the channel at *available* interval. An important distinction is that the transmission may be carried out in the first interval if the remaining of the current interval is sufficient to carry out the transmission (e.g. $\Phi_7 \geq s_b$ for packet P_1 in Fig. 3). This occurs with probability p, otherwise, transmission succeeds at the n^{th} retry and the service time includes n *busy* and $n-1$ *available* intervals (e.g. $\Phi_1 \leq s_b$ for packet P_2 in Fig. 3). Therefore, we have

$$S_V = \begin{cases} s_b & \text{with prob. } p, \\ \Phi_j + \sum_{i=1}^{n} T_{j+2i} + \sum_{i=1}^{n-1} T_{j+2i-1} + s_b & \text{with prob. } 1-p. \end{cases} \tag{20}$$

Similar to (15), the following equations can be derived (we set $j = 0$ for notation convenience):

$$\begin{aligned}\mathbb{E}[B] &= \mathbb{E}[\underbrace{T_{2n} + \sum_{i=1}^{n-1}(T_{2i-1} + T_{2i})]}_{B} \\ &= \mathbb{E}[A] + u = (1/p - 1)(u + v_e) + u, \\ \mathbb{E}[B^2] &= \mathbb{E}[\big(T_{2n} + \sum_{i=1}^{n-1}(T_{2i-1} + T_{2i})\big)^2] \\ &= \mathbb{E}[A^2] + \mathbb{E}[T_{2n}^2] + 2u\mathbb{E}[A] \\ &= (1/p - 1)(2u^2 + \\ &\frac{-(s_b^2 + 2vs_b + 2v^2)e^{-s_b/v} + 2v^2}{1 - e^{-s_b/v} + 2uv_e}) \\ &+ (\frac{2-p}{p^2} + \frac{3}{p} + 2)(u + v_e)^2 + 2u^2 \\ &+ 2u(1/p - 1)(u + v_e). \end{aligned} \tag{21}$$

with v_e defined in (16). We also note that the distribution and moments of Φ can be found similar to Ω in (13) after replacing u by v, which yields the following equations:

$$\begin{aligned}\mathbb{E}[\Phi] &= \frac{v - (s_b + v)e^{-\frac{s_b}{v}} + (s_b^2/v)E_1(\frac{s_b}{v})}{2(1 - e^{-\frac{s_b}{v}} + \frac{s_b}{v}E_1(\frac{s_b}{v}))}, \\ \mathbb{E}[\Phi^2] &= \frac{2v^2 - (s_b^2 + 2s_bv + 2v^2)e^{\frac{-s_b}{v}} + (s_b^3/v)E_1(\frac{s_b}{v})}{3(1 - e^{-\frac{s_b}{v}} + \frac{s_b}{v}E_1(\frac{s_b}{v}))}, \end{aligned} \tag{22}$$

where $E_1(x) = \int_x^\infty e^{-t}/tdt$, is called the exponential integral. In practice, a single packet transmission time is much smaller than the mean channel availability of primary wireless networks (i.e. $s_b/v \to 0$) [36]–[38]. Using the approximation $e^{-s_b/v} \approx 1 - s_b/v$ and noting $E_1(s_b/v) \to \infty$, the above equations are simplified to:

$$\mathbb{E}[\Phi] = s_b/2,\ \mathbb{E}[\Phi^2] = s_b^2/3 \Rightarrow \sigma_\Phi^2 = s_b^2/12. \tag{23}$$

For notation convenience we use (21) in the rest of this section. Combining (18), (19) and (21) results in the following Expected value for S_V:

$$\begin{aligned}\mathbb{E}[S_V] &= ps_b + (1-p)\mathbb{E}[\Phi_j + B + s_b] \\ &= s_b + (1-p)(s_b/2 + \mathbb{E}[B]), \\ \mathbb{E}[(S_V)^2] &= ps_b^2 + (1-p)\mathbb{E}[(\Phi_j + B + s_b)^2] \\ &= s_b^2 + (1-p)\big(4s_b^2/3 + \mathbb{E}[B^2] \\ &+ 3s_b\mathbb{E}[B]\big). \end{aligned} \tag{24}$$

The service time to transmit a single packet S_1 is a bimodal random variable with two components S_U and S_V with moments provided in (17) and (22), respectively. Substituting (17) and (22) in (10) results in the following moments for S_1:

$$\begin{aligned}\mathbb{E}[S_1] &= \frac{u}{u+v}\mathbb{E}[S_U] + \frac{v}{u+v}\mathbb{E}[S_V] \qquad (\textit{light} \text{ traffic regime}) \\ &= \frac{u}{u+v}\big(s_b + \frac{u}{2} + \mathbb{E}[A]\big) \\ &+ \frac{v}{u+v}\big(s_b + (1-p)(s_b/2 + \mathbb{E}[B]\big), \\ \mathbb{E}[S_1^2] &= \frac{u}{u+v}\mathbb{E}[(S_U)^2] + \frac{v}{u+v}\mathbb{E}[(S_V)^2] \\ &= \frac{u}{u+v}\big[s_b^2 + 2\frac{u^2}{3} + \mathbb{E}[A^2] \\ &+ s_bu + (2s_b + u)\mathbb{E}[A]\big] \\ &+ \frac{v}{u+v}\big[s_b^2 + (1-p)\big(4s_b^2/3 \\ &+ \mathbb{E}[B^2] + 3s_b)\mathbb{E}[B]\big)\big]. \end{aligned} \tag{25}$$

2) Heavy traffic regime: In this regime, the majority of packets are buffered before transmission. Consequently, the packet in the frontier of the queue becomes available for transmission right after the departure of the previous packet, while the channel is still in *available* state. Thus, the state B in the state transition diagram depicted in Fig. 4 (b), fades away in steady state conditions. Therefore, the remaining states include: i) state A, where the packet meets an *available* interval and completes its transmission and ii) state C, where the remaining of the current *available* interval is not sufficient to carry out a complete packet transmission. These two situations are depicted as case 1 in Fig. 3 (Packets P_1 and P_2). We, also note that considering the memory-less property of exponential distribution for channel intervals implies that the probability of transition to states A and C is regardless of the previous state. Therefore, the distribution of service time in *heavy* traffic regime is similar to the derived equation in (18) for S_V in *light* traffic regime noting the obtained distributions for Φ. The main difference is that in contrast to the *light* traffic mode, where the transmission epoch is chosen uniformly, here, a packet transmission starts right after successful delivery the preceding packet. However, the resulting distributions are equivalent thank to the memoryless property of the interval length distribution. The probability of continuation of the channel availability for additional t seconds after a time epoch is independent of its history, no matter how this epoch is chosen. Consequently, we have:

$$\begin{aligned}&f_{S_1}(s)[\text{in } \textit{heavy} \text{ traffic regime}] = \\ &f_{S_V}(s)[\text{in } \textit{light} \text{ traffic regime derived in (18) with a new } \Phi], \\ &\mathbb{E}(S_1^k)[\text{in } \textit{heavy} \text{ traffic regime}] = \\ &\mathbb{E}(S_V^k)[\text{in } \textit{light} \text{ traffic regime derived in (22) with a new } \mathbb{E}[\Phi^k]]. \end{aligned} \tag{26}$$

The equations in (23) and (24) correspond to the time required for transmitting a single copy of the packet, S_1, respectively in *low* and *heavy traffic regimes*. Once the packet is received at the destination, its integrity is checked with an error checking mechanism (e.g. CRC codes) and notify the transmitter with Acknowledge message (ACK) using an error-free instantaneous feedback channel.

[1] Here, we assume zero error tolerance, meaning that a packet is considered in error even if a single bit is flipped. Hence the packet error probability is $\beta_P = 1 - \alpha^{kN+H}$, where $\alpha = 1-\beta$ is the successful bit transmission probability. Therefore, the number of transmissions R follows a Geometric distribution with success parameter $\alpha_P = 1 - \beta_P$:

$$\begin{aligned}\mathbb{P}r(R = n) &= (\beta_P)^{n-1}(1-\beta_P) \\ &= \big[(1-\beta)\beta^{n-1}\big]^{kN+H}.\end{aligned} \tag{27}$$

The service time including potential retransmission is:

$$S = \sum_{i=1}^{R} S_i \ , \tag{28}$$

where S_i and R are independent and distributed according (10) and (25), respectively. Therefore, we have the following expressions for the moments of service time:

$$\begin{aligned}\mathbb{E}[S] &= \mathbb{E}_R\big[\mathbb{E}_{S|R}[S|R]\big] \\ &= \mathbb{E}_R\big[R\mathbb{E}_{S_i|R}[S_i|R]\big] = \mathbb{E}_R[R]\ \mathbb{E}_{S_i}[S_i] \\ &= \frac{1}{\alpha_P}\mathbb{E}[S_1],\end{aligned} \tag{29}$$

$$\begin{aligned}\mathbb{E}[S^2] &= \mathbb{E}_R\big[\mathbb{E}_{S|R}[S^2|R]\big] \\ &= \mathbb{E}_R\big[\sum_{i=1}^{R}\mathbb{E}_{S_i}[S_i^2] \\ &+ 2\sum_{i=1}^{R}\sum_{j=1,j\neq i}^{R}\mathbb{E}[S_i]\mathbb{E}[S_j]\big] \\ &= \mathbb{E}_R\big[R\mathbb{E}[S_i^2] + R(R-1)(\mathbb{E}[S_i])^2\big] \\ &= \mathbb{E}[R]\mathbb{E}[S_i^2] + \mathbb{E}[R(R-1)](\mathbb{E}[S_i])^2 \\ &= \frac{1}{\alpha_P}\mathbb{E}[(S_1)^2],\end{aligned} \tag{30}$$

where we used pairwise independence of S_i as well as their independence from R. Finally, the variance and coefficient of variation of service time, denoted by C_S, are obtained as follows:

$$\sigma_S^2 = \mathbb{E}[S^2] - \big(\mathbb{E}[S]\big)^2, \tag{31}$$

$$C_S^2 = \frac{\sigma_S^2}{\big(\mathbb{E}[S]\big)^2} = \frac{\mathbb{E}[S^2]}{\big(\mathbb{E}[S]\big)^2} - 1. \tag{32}$$

[1]One may consider the impact of ACK messages. For instance, in a stop-and-wait implementation, a packet transmission attempt occurs right after the reception of ACK message or after the expiration of ACK timer. In this case, if the Ack messages are of length L_f, and the feedback channel is of rate R_f with bit error probability of β_f, a packet transmission considered successful if both packet and Ack message are delivered error-free (i.e. $P_{\text{success}} : (1-\beta)^{KN+H} \to (1-\beta)^{KN+H}(1-\beta_f)^{L_k}$). The additional time imposed on the service time due to ACK messages is equal to L_f/R_f when the ACK message receives successfully with probability $(1-\beta_f)^{L_k}$ and is equal to T_f, when the ACK message encounters transmission error with probability $1-(1-\beta_f)^{L_k}$ (i.e. $E[S_1] \to E[S_1] + (1-\beta_f)^{L_k}L_f/R_f + (1-(1-\beta_f)^{L_k})T_f$).

[1]we note that if the Ack messages are of length L_f, and the feedback channel is of rate R_f, and bit error probability of β_f, a packet can be discarded due to error in the packet itself or loosing the Ack message. Therefore, $P^*_{\text{success}} \to (1-\beta)^{KN+H}(1-\beta_f)^{L_k}$ and $E[s1^*] = E[s1] + L_f/R_f + T_f(1/(1-P^*_{\text{success}}))$.

C. Waiting time

Another source of delay is waiting time (W), which is the time each packet spends in the queuing system until it reaches the frontier of the queue after departure of preceding packets. For the *light traffic regime*, this delay is almost negligible as mentioned earlier. Calculating the accurate waiting time for GI/GI/1 queuing system is complex in general and involves obtaining the queuing transition kernel [39]. However, there are simplifying approximations. Here, we use the celebrated Kingman's 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 interarrival times are independent [40]. Packet interarrival 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 the sample arrival process. Therefore, the arrival process is independent from the service process allowing us to use the following Kingman's equation.

$$\mathbb{E}[W] \approx \frac{\rho}{(1-\rho)}\frac{\mathbb{E}[S](C_S^2 + C_\tau^2)}{2}, \tag{33}$$

where $\rho = \mathbb{E}[\mathbf{S}]/\mathbb{E}[\tau]$ is the queue utilization factor. Using equations (2) and (27), we have

$$\begin{aligned}\rho &= \mathbb{E}[S]/\mathbb{E}[\tau] \\ &= \frac{\lambda}{k\alpha_P}\Big[\frac{u}{u+v}\big(s_b + \frac{u}{2} + (1/p-1)(u+v_e)\big) \\ &+ \frac{v}{u+v}\Big(s_b + (1-p)\big(v_e/2 \\ &+ (1/p-1)(u+v_e)+u\big)\Big)\Big]\end{aligned} \tag{34}$$

for the *heavy traffic regime*.

D. Age of Information

The age of information D_j for a measurement sample X_j is defined as the timespan from the sampling epoch until it is successfully delivered to the destination. For the proposed system model, if sample j is bundled into packet P_i, then 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 (W_i) and iii) service time to transmit the packet (S_i) (summation of delay terms ii and iii is usually called end-to-end delay). Thus, the age of information for sample j is defined as

$$D_j = \bar{F}_i + W_i + S_i, \ \text{for}\ (i-1)k < j \leq ik. \tag{35}$$

Under stability conditions ($\rho < 1$), in steady state situation, the expected age of information for a sample can be obtained from $\mathbb{E}[D] = \mathbb{E}[D_i]$ and we have:

$$\begin{aligned}\mathbb{E}[D] &= \mathbb{E}[\bar{F}] + \mathbb{E}[W] + \mathbb{E}[S] \\ &\approx \frac{k-1}{2\lambda} + (\frac{\rho}{1-\rho}\frac{(C_S^2 + C_\tau^2)}{2} + 1)\mathbb{E}[S]\end{aligned} \tag{36}$$

for *heavy traffic regime*. In *light traffic regime*, waiting time is negligible and it reduces to

$$\mathbb{E}[D] = \mathbb{E}[\bar{F}] + \mathbb{E}[W] + \mathbb{E}[S] \approx \frac{k-1}{2\lambda} + \mathbb{E}[S]. \quad (37)$$

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

$$\mathbb{E}[D] = \mathbb{E}[D_i] = \lim_{t\to\infty} \frac{1}{n(t)} \sum_{i=1}^{n(t)} D_i, \quad (38)$$

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

E. Extension to multiple sensor system

We note that merging multiple queues with independent Poisson arrival processes yields a Poisson process with a rate equal to the summation of the rates of individual queues [39]. However, since the resulting packet arrival process for each sensor in the proposed method exhibits Gamma distributed interarrival times, we can not simply replace the cluster of m sensors with one sensor with sample arrival rate of $m\lambda$. Therefore, we need to characterize the impact of potential collisions and multiple arrival processes on the derived equations.

The impact of using multiple sensors on energy efficiency is straightforward. The only change is to incorporate the packet discard rate due to inter-sensor collisions in the overall transmission rate. If a coordinate access method such as polling, token based or reservation based channel access is utilized, the equation (6) remains unchanged and only the numeric value of energy consumption per packet P_p shall be updated to include the cost of the utilized channel coordination method [41]. However, if a collision based random access method is implemented with collision probability p_c, the retransmission rate R derived in (25) should be updated. For instance, in Aloha system with m users, packet transmission time s_b, and packet arrival rate λ/k, a simultaneous transmission by any of the other $m-1$ sensors in time interval $[T-s_b, T+s_b]$ causes collision for a packet with departure epoch T. The transmission during interval of length $2s_b$ occurs with probability $p_t = 2\lambda s_b/k$. Therefore, the probability of collision according to [42] is:

$$p_c(k) = 1 - mp_t(1-p_t)^{m-1} \quad (39)$$
$$= 1 - m(\frac{\lambda s_b}{k})(1-\frac{\lambda s_b}{k})^{m-1}.$$

A packet is discarded if it collides with other sensors' transmissions or due to channel errors. Consequently, the updated packet discard rate $\acute{\beta}_P = p_c + (1-p_c)\beta_P$ should be used in (25) to obtain retransmission rate, which in turn updates the energy efficiency in (6).

In order to investigate the impact of the number of employed sensors on the age of information, we consider both collision based and coordinated access methods. If a collision based method such as Aloha is used, the expected service time is prolonged due to higher retransmission rate caused by inter-sensor collisions. We need to replace α_P with $\acute{\alpha}_P = 1-\acute{\beta}_P = 1-p_c-(1-p_c)\beta_P$ in (27) and (28) to update the moments of the service time. As a special case, if the total packet arrival rate of $m\lambda/k$ is much less than the service rate $1/\mathbb{E}[S]$, then the probability of collision is negligible $p_c \approx 0$ and no additional delay is imposed on the packets. If a coordinated access method (e.g. polling method) is employed, simultaneous transmission are prohibited, but an additional delay is imposed to the age of information, which accounts for the waiting time for each sensor to take transmission turn. Since the expected transmission time for each packet including retransmissions is $s_b\mathbb{E}[R] = \frac{kN+H}{R_{ch}(1-\beta_P)}$ and each packet waits for $(m-1)/2$ sensors on average to take transmission turn, the additional imposed delay is approximately $\frac{(m-1)(kN+H)}{2R_{ch}(1-\beta_P)}$.

V. Simulation Results

In this section, we present simulation results in order to examine the energy and delay performance behavior of the proposed method. We first state the simulation setup details and then elaborate on the details of the results.

A. Simulation setup

In the following simulations, we generate random measurement samples using a Poisson process with arrival rate of λ for each of the m sensors. We vary the framing number k and calculate the required delay and power consumption terms. We use Monte Carlo method and use the time averages as surrogates for the statistical means of random variables noting the ergodicity of the queue under stability conditions. To obtain accurate results, for any choice of framing parameter k, the number of samples is chosen 10^5 or chosen such that the number of resulting packets is at least 10^4, whichever is larger (i.e. $N_S = \max(10^5, k \times 10^4)$. In order to ensure that the time averages for delay terms reflect the steady state operation of the queuing system under stability conditions, we take the average only over the last 50% of the simulated packets to discard the initial transitions. Likewise, we generate channel intervals with alternating *available* and *busy* states for the time required to transmit all the simulated packets. Finally, to obtain more accurate results and avoid biasing to initializations, for each scenario, we repeat the simulation for 4 times and take the average over the results of all runs. We investigate both conventional (full channel access) and cognitive sensor scenarios with opportunistic channel access.

B. Results

Fig. 5 presents variations of different delay terms ($\bar{F}$, S, W and D) versus the framing parameter k for the proposed communication system under *heavy traffic regime*. The averaged packet formation delay $\mathbb{E}[\bar{F}]$ (black curve) is an increasing function of k, since the framing module waits longer to collect more measurement samples to form a data packet, therefore the average packet formation time per sample is longer as equation (9) suggests. Likewise, the expected inter-packet

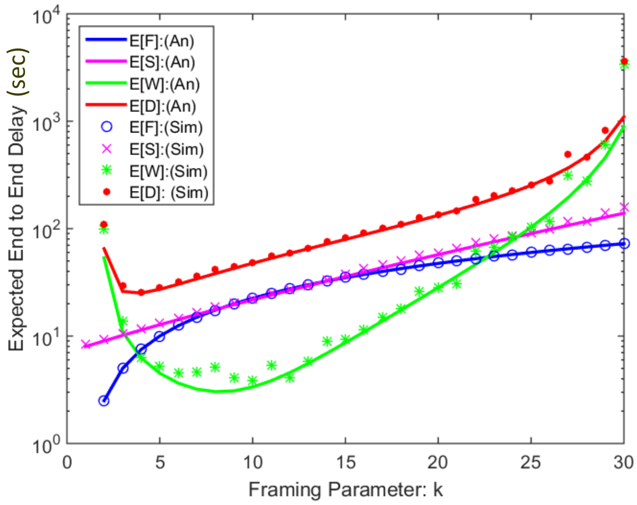


Fig. 5: Comparison between the simulations (denoted by Sim) and analytical derivations (denoted by An) for different delay terms for the proposed framing policy under full channel access. The simulation parameters are $\lambda = 0.2$ sample/sec, $N = 8$ bits, $H = 128$ bits, $R_{ch} = 100$ bps, $\beta : 10^{-4}$.

arrival time $\mathbb{E}[\tau]$ increases with k. Similarly, increasing k results in longer packets, which in turn increases the average service time $\mathbb{E}[S]$ as was expected. The rate of variation of service time S is lower than the one of τ in this figure, 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 $\rho = \mathbb{E}[S]/\mathbb{E}[\tau]$ decreases with k and hence the packets experience shorter waiting times $\mathbb{E}[W]$ in the queue. However, there is another impact for a large k that works in the opposite direction. Enlarging the packet lengths $l(k) = kN + H$, exponentially increases the packet error rate and consequently increases the rate of retransmissions $\mathbb{E}[R]$ in (25), which in turn implies that service time $\mathbb{E}[S]$ grows faster than that of an error-free system and hence the utilization factor $\rho = \mathbb{E}[S]/\mathbb{E}[\tau]$ increases. Consequently, the packets spend longer times in the queue. These opposite impacts result in a valley-shaped functionality for $\mathbb{E}[W]$ and hence for $\mathbb{E}[D]$ with respect to k. Therefore, there is an optimal value for k that minimizes the average age of information. Fig. 5 exhibits a perfect match between the analytically derived terms and the numerically obtained simulation results, which confirms the accuracy of analytical derivations. The minor mismatch for waiting time (green curve) is due to the well-known approximation in the Kingman's formula. However, the impact of this approximation on the age of information (red curve) is negligible.

Fig. 6 presents the behavior of expected service time $\mathbb{E}[S]$ with varying channel unavailability factor $\rho_{ch} = u/v$. We note that service time is defined as the time span from the epoch that a packet becomes ready for transmission until the completion of transmission. For small ρ_{ch} values, the system approaches the conventional communication systems with full channel access. Therefore, service time for a packet of length $kN + H$ increases with k. However, for high ρ_{ch} values,most

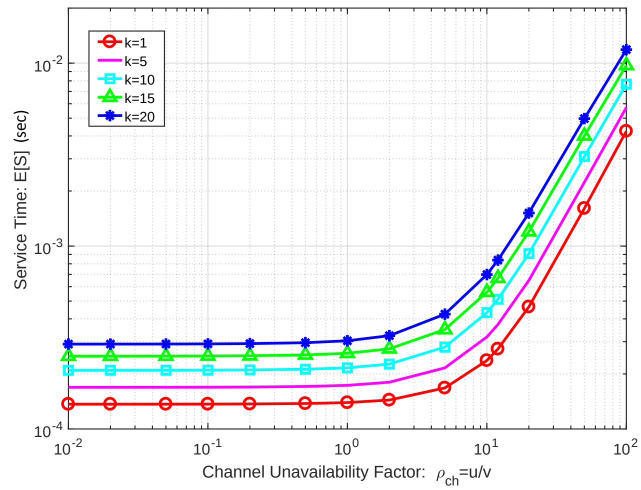


Fig. 6: Service time $\mathbb{E}[S]$ is plotted versus framing parameter k for different channel unavailability ratio $\rho_{ch} = \frac{u}{v}$. Simulation parameters are $\lambda = 30$ sample/sec, $N = 8$ bits, $H = 64$ bits, $\beta = 10^{-6}$, $R_{ch} = 10^6 bps$.

packets arrive at *busy* interval and hence the dominant term is the waiting time for the shared channel to be released by the PUs. The expected value of this term is approximately $u/2$, which is proportional to u/v that for fixed v. Therefore $\mathbb{E}[S]$ is linearly proportional to ρ_{ch} as shown in Fig. 6.

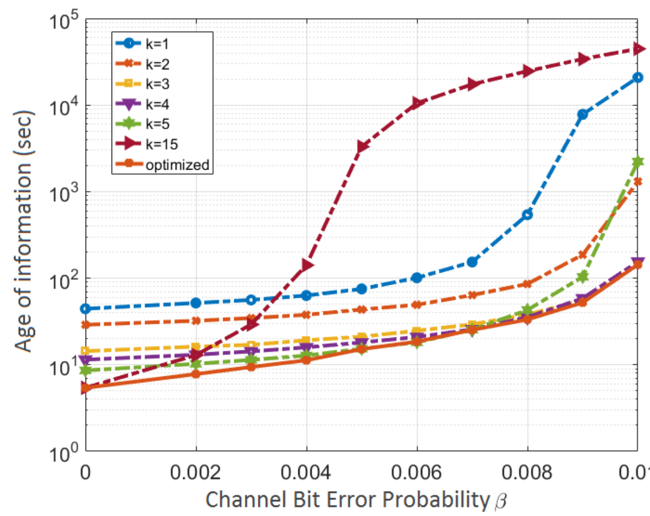


Fig. 7: Comparison between the proposed method of adaptive packet length and the conventional systems with fixed packet lengths. The simulation parameters are $\lambda = 0.2$ sample/sec, $N = 8$ bit, $H = 128$ bit, $R_{ch} = 100bps$.

Fig. 7 compares the age of information for the proposed system with adaptive packet lengths against a conventional system with constant packet length. In this scenario, we simulate slow varying channels, where the channel bit error probability β varies gradually from $\beta = 0$ to $\beta = 10^{-2}$. For a conventional system, we try different numbers of samples in the packet ($k = 1, 2, 3, 4, 5, 15$). The proposed method outperforms the conventional system in terms of the expected age of information, since for any choice of channel error probability, it selects the optimal k. Apparently, the system outperforms the average of all conventional systems as well.

Fig. 8 represents the results for transmission energy consumption rate (inverse of energy efficiency) for the system with a constraint on the expected age of information. The figures in the left and right hand sides show the age of information and energy efficiency for (a) *heavy traffic regime* and (b) *light traffic regime*, respectively. The energy consumption rate for both schemes exhibit a cup shape convex functionality. The most energy efficient points can be easily found by setting the derivative of the energy efficiency in (6) to zero ($\partial EE/\partial k = 0$) or by applying numerical methods such as gradient descent to find $k_{\text{global}} = \underset{k}{\text{argmin}}\{1/EE(k)\}$. However, maximal energy efficiency may not be achievable if the age of information is constrained.

We note that in *heavy* traffic mode, for extremely small k, the header overhead is large and hence the input rate may exceed the service rate. Consequently, the age of information approaches infinity duo the instability of the queue. This does not occur for *light* traffic mode. Under constraints on the age of information as in (7), the condition ($\mathbb{E}[D] \leq D_0$) defines the feasible range for k. Since the expected age of information $\mathbb{E}[D]$ does not satisfy convexity check in general, techniques such as Karush–Kuhn–Tucker (KKT) conditions are not applied. However, inspired by KKT method, and noting the piece-wise monotonicity of $\mathbb{E}[D]$, we first obtain the global optimum for energy efficiency k_{global} as mentioned above. Then, we find the feasible region $[k_{\text{min}} \leq k \leq k_{\text{max}}]$ by identifying the corner points $k_{\text{min}} = \min\{k : k \in \{1, 2, \dots\}, \mathbb{E}[D] \leq D_0\}$ and $k_{\text{max}} = \max\{k : k \in \{1, 2, \dots\}, \mathbb{E}[D] \leq D_0\}$. If the global optima falls in the feasible region, where the constraint satisfies (e.g. Fig. 8.a), we choose the global optima, otherwise one of the corner points (k_{min} or k_{max}) with higher energy efficiency is selected (e.g. Fig. 8.b). In scenario (a), $D_0 = 10$ is chosen as the minimum acceptable expected age of information, which resulted in the feasibility range of $3 \leq k \leq 21$ for k. Since the global optima for energy efficiency ($k_{\text{global}} = 10$) is within the feasible range, it is selected as the output of constrained optimization. However, in case (b), the feasible range for $\mathbb{E}[D] \leq D_0 = 1.5$ is $1 \leq k \leq 3$. Since the global optima for energy efficiency occurs for $k_{\text{global}} = 6$, which is out of the feasible range, $k_{\text{max}} = 3$ is reported as the solution of the optimization problem.

TABLE I: Optimal framing number k for energy efficiency a cluster of m cognitive sensors for different channel bit error probability β. The simulation parameters are $\lambda = 1$ sample/sec, $N = 8$ bits, $H = 32$ bits, $R_{ch} = 1000$ bps, $\rho_{ch} = u/v = 2$, $1 \leq k \leq 100$.

β \ m	2	3	4	5	10	15	20	50
$\beta = 10^{-5}$	33	45	55	63	93	100	100	100
$\beta = 10^{-4}$	11	14	17	20	29	36	42	66
$\beta = 10^{-3}$	3	5	5	6	9	11	13	21
$\beta = 10^{-2}$	1	1	2	2	3	4	4	6

The optimal framing number k for a cluster of m cognitive sensors are provided in Table I. It is noticeable that the systems tends to choose smaller packet sizes for higher error probabilities. This behavior is to compensate the high packet discard rates by squeezing the packet sizes. Also, it is seen that as the number of sensors grows, the proposed optimization method tends to choose a larger k and include a higher

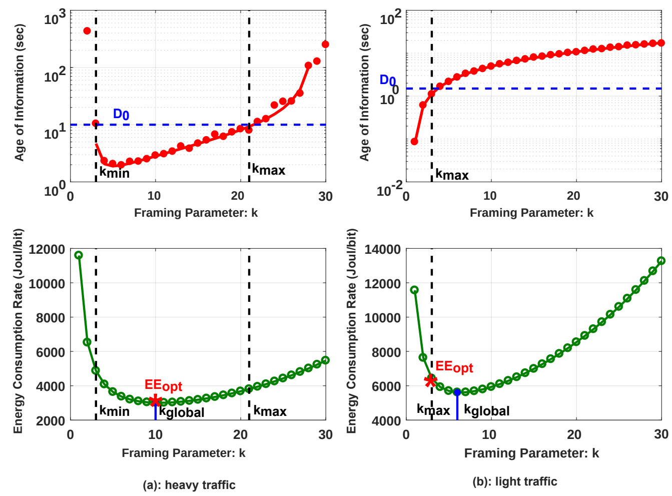


Fig. 8: Energy efficiency under delay constraints for (a): *heavy traffic regime* with $\lambda = 5$ sample/sec and $R_{ch} = 800$ bps and (b): *light traffic regime* with $\lambda = 1$ sample/sec and $R_{ch} = 10^3$ bps. The rest of simulation parameters are $N = 6$ bits, $H = 80$ bits, $u = 1$ sec, $v = 2$ secs, $\beta = 10^{-2}$.

number of samples into each transmission packet. When more sensors are utilized, the system tend to compensate the high collision rate p_c by reducing concurrent transmission rate $p_t = \frac{2\lambda s_b}{k} = \frac{2\lambda(kN+H)}{kR_{ch}} = \frac{2\lambda N}{R_{ch}} + \frac{2\lambda H}{kR_{ch}}$ as mentioned in section IV-E. Therefore, it chooses higher k values.

VI. Concluding Remarks

In this paper, we proposed an implementation of cognitive sensor networks, where a cluster of unlicensed sensors opportunistically transmit their measurement samples to a common sink node by exploiting the vacancies of a shared channel. An adaptive framing policy is developed by assessing the impact of packet lengths on energy efficiency and the age of information. The idea is to regularize packet lengths for secondary nodes based on the sensing parameters (sensing rate λ, and the number of bits per sample N), communication parameters (the number of header bits per packet H, and channel rate R_{ch}) as well as the current channel quality factors (channel utilization process parameters by primary nodes u, v and channel error rate β).

As a general trend, longer packets are desired for error-free channels since they improve the energy efficiency by reducing the average header bits per sample. In erroneous channels, however, longer packets increase packet discard rate. Due to these opposite facts, there exists an optimal value for k as shown in Fig. 8. The impact of packet lengths on the age of information is more involving and depends on the input traffic mode. In the *light* traffic regime, where queuing delay is negligible, shorter packets are preferred to reduce the samples' waiting time for packet formation. However, in the *heavy* traffic regime, longer packets experience higher discard rates, which in turn increase the service and waiting time in the queue. Therefore, an optimal number of samples per packet should be chosen properly. When multiple secondary sensors are employed, the collision rate is reversely proportional with the number of sample in the packets (k) (since packet rate decreases with k). Therefore, the system prefers longer packets. Finally, we note that the packet transmission times should be much smaller than the mean *available* interval ($s_b \ll v$) to avoid frequent transmission interruptions by the primary users.

This proposed joint framing and scheduling policy can be used to implement a low-cost and optimized network of cognitive sensor networks for a wide range of applications with dynamic channel quality conditions and opportunistic access to shared channels. If the channel variation is much slower than the single packet transmission rate, this scheme can also be used to adaptively adjust the framing policy for time-varying shared channels.

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