Power Minimization Through Packet Retention in Cognitive Radio Sensor Networks Under Interference and Delay Constraints: An Optimal Stopping Approach

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Abstract. We consider the problem of power minimization in Cognitive Radio Sensor Networks (CRSN). The aim of this paper is twofold: First, we study the problem of packets retention in a queue with the aim of minimizing transmission power in delay-tolerant applications. The problem is classified as an optimal stopping problem. The optimal stopping rule has been derived as well. Optimal number of released packets is determined in each round through an Integer Linear Programming (ILP) optimization problem. This transmission paradigm is tested via simulations in an interference-free environment leading to a significant reduction in transmission power (at least 55%). Second, we address the problem of applying the scheme of packets retention through the Optimal Stopping Policy (OSP) to underlay CRSN where strict interference threshold does exist. Also, this problem is subjected to a delay constraint. Optimal number of released packets at this case is determined through another knapsack optimization problem that takes interference to Primary User (PU) into account. Extensive simulations that encompass dropped packet rate, Average Power per Transmitted Packet (APTP) and average consequent delay have been proposed. Simulations proved that our scheme outperforms traditional transmission method as far as dropped packet rate and APTP are substantially concerned, where end to end delay could be tolerated.

Keywords: Cognitive radio · Sensor network · Optimal stopping rule

1 Introduction

Due to the wide proliferation of mobile communication, there is an inevitable rapid growth in mobile traffic leading to the problem of spectrum scarcity. However, many spectrum studies showed that huge part of the spectrum is underutilized. This, consequently, led to the concept of Cognitive Radio (CR) [1] which received a great attention to alleviate the spectrum scarcity problem. It enables unlicensed users to communicate over the licensed bands assigned

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for the licensed users through one of two modes. First: Spectrum Sharing (SS), or underlay, where CR Secondary Users (SU) can operate on same bands licensed for PU provided that sufficient interference thresholds to PU are strictly maintained. Second: Opportunistic Spectrum Access (OSA), or overlay, where SU can dynamically exploit spectrum holes when PU are inactive [2]. Wireless Sensor Networks (WSN) have gained a great attention as a research area [3]. Due to the hardness of rechargeability of these networks, they have limited energy budget and hence a limited lifetime. Therefore, a considerable amount of research work has been exerted to mitigate the problem of energy limitation in WSN. Accordingly, energy minimization and lifetime maximization of WSN have been investigated in many research papers [4–7]. CRSN is a research trend that enables WSN to work in cognitive way. The essence of CRSN, its basic design principles, different architectures, applications, advantages and shortcomings have been well introduced in [8].

In this paper, we are concerned about energy minimization through formulation of an optimal stopping problem and finding out its stopping rule. Optimal stopping is concerned with the problem of taking a specific action at specific time based on sequentially observed previous states so as for maximizing the payoff, or minimizing the cost, or both. With the optimal stopping problem, there always exists an optimal stopping rule, where the decision is taken based on it. This type of problems usually arises in areas of statistics, where the action is taken with the aim of testing an hypothesis or estimating a parameter. Considering seminal and recent work, optimal stopping theory has been applied to opportunistic scheduling [9] and spectrum sensing [10],[11], but not to power minimization; which is the problem we will consider in this context. In[9], the authors studied optimal transmission scheduling policies in cognitive radio networks. They proposed a cooperative scheme that improves the primary network performance and allows secondary nodes to access the licensed spectrum in order to cooperate. In [10], the authors studied joint channel sensing and probing scheme and they proved that this scheme can achieve significant throughput gains over the conventional mechanism that uses sensing alone. However, in [11], authors studied the problem of optimizing the channel sensing parameters in the presence of sensing errors. They proposed suboptimal solutions that significantly reduce the complexity and maintain a near-optimal throughput. In this paper we apply the optimal stopping policy to the problem of power minimization in underlay cognitive radio sensor networks under interference and delay constraints.

The rest of this paper is organized as follows. Power minimization through packets retention via the optimal stopping approach is studied in Sect. 2, where the problem is formulated and the stopping policy is derived as well. In Sect. 3, the power minimization problem derived in Sect. 2 is extended to CRSN where interference threshold to PU does exist. Evaluating our performance is conducted through a simulation study which proves that our scheme through packets retention via OSP performs better than traditional transmission method as far as

APTP and successful packet reception are concerned. Finally, Sect. 4 concludes the paper.

2 Power Optimization Through Optimal Stopping Policy

2.1 Problem Formulation and Stopping Rule Derivation

In this paper, we focus on the problem of minimizing transmission power of nodes of any network through packet retention in a queue. Each node observes its power status round by round. Based on the observation sequence, it decides whether it sends its packet(s) instantaneously or further keeps it/them in the queue. To minimize the transmission power, each node makes the decision based on the result of comparing the instantaneous cost and the expected cost of future observations. The instantaneous cost is represented by the instantaneous power consumed if the packet is transmitted instantly. It depends directly on the instantaneous channel quality at this round for the observed nodes. On the other hand, the expected cost of future observations is the expected power the node will consume if it keeps the packet for more rounds taking into consideration how many packets are already existing in the queue. Consequently, this issue can be formulated as a sequential decision problem and can be investigated by applying the optimal stopping theory.

We are following the communication model presented in [4], the total power consumption consists of two components: power consumption of the amplifiers P_{PA} which depends on transmission power P_t with the relation

$$P_{PA} = (1 + \alpha)P_t. \tag{1}$$

where $\alpha = \frac{\xi}{\eta} - 1$ with η the drain efficiency of the power amplifier and ξ the peak-to-average power ratio(PAR), which depends on the modulation scheme and the associated constellation size. Transmission power P_t is given by the link-budget relationship, when the channel experiences a square-law path loss

$$P_t = \overline{E_b} \times \frac{R_b(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f. \tag{2}$$

where $\overline{E_b}$ is the required energy per bit for a given BER requirement, R_b is the bit rate of the RF system, d is the transmission distance. G_t and G_r are the antenna gain of the transmitter and the receiver respectively, λ is the carrier wavelength, M_l is the link margin compensating the hardware process variations and other additive background noise or interference, N_f is the receiver noise figure defined as $N_f = \frac{N_r}{N_0}$ with N_0 the single-sided thermal noise power spectral density (PSD) at room temperature and N_r is the PSD of the total effective noise at the receiver input.

The other term in the total power consumption is the circuit power P_c. Finally, this gives the total energy consumption per bit as

$$E_{bt} = \frac{P_{PA} + P_c}{R_b}. \tag{3}$$

The instantaneous required BER per-packet, assuming BPSK modulation scheme is used, is also given by

$$\overline{P_b} = Q(\sqrt{2\gamma_b}) = e^{-\gamma_b} = e^{-\frac{\overline{E_b}|H|^2}{N_0}} \tag{4}$$

where $|H|^2$ is the instantaneous squared magnitude of the channel. Substituting from (4) into (2), and rearranging, we get the transmission power per node as follows

$$P_t = -ln(2\overline{P_b}) \times \frac{N_0}{|H|^2} \times \frac{R_b(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f \tag{5}$$

Hence, and without loss of generality, we will consider only transmission power in our analysis as circuit power is, more or less, a constant that depends on the circuitry.

From now on, Q is defined as the queue size (Maximum number of packets could be kept) for each node in the network, and k is defined as the number of packets in the queue at round i. We intend to solve the stopping problem discussed above to minimize the cost represented by power by deriving an optimal rule that decides when to stop waiting for next rounds and transmit the packet(s) in the current round. Denote by ${X_i}^{(k)}$ the minimum cost the node can achieve at round i when k packets are in the queue.

$${X_i}^{(k)} = \min\{P^k_{t_i}, E\{\min(P^{k+1}_{t_{i+1}}, P^{k+2}_{t_{i+2}}, ..., P^Q_{t_{i+Q-k}})\}\} \tag{6}$$

where $P^k_{t_i}$ represents the instantaneous cost in round i (after the i^{th} observation) when k packets are already existing in the queue. Also, $E\{\min(P^{k+1}_{t_{i+1}}, P^{k+2}_{t_{i+2}}, ..., P^Q_{t_{i+Q-k}})\}$ represents the expected cost resulted by proceeding to keep the packet for next rounds till the queue is full. Inside the expectation operator, the minimum power scenario for keeping packets has to be chosen. To calculate $E\{\min(P^{k+1}_{t_{i+1}}, P^{k+2}_{t_{i+2}}, ..., P^Q_{t_{i+Q-k}})\}$, we make the following mathematical analysis:

$$E\{\min(P^{k+1}_{t_{i+1}}, P^{k+2}_{t_{i+2}}, ..., P^Q_{t_{i+Q-k}})\} = E\{\frac{1}{\max(\frac{1}{P^{k+1}_{t_{i+1}}}, \frac{1}{P^{k+2}_{t_{i+2}}}, ..., \frac{1}{P^Q_{t_{i+Q-k}}})}\} \tag{7}$$

Furthermore, since the function inside the expectation operator of (7) is a convex one ($f(x) = \frac{1}{x}$ is a convex function) [12], Jensen's inequality can be applied:

$$E\{\frac{1}{\max(\frac{1}{P^{k+1}_{t_{i+1}}},\frac{1}{P^{k+2}_{t_{i+2}}},.....,\frac{1}{P^{Q}_{t_{i+Q-k}}})}\} \geq \frac{1}{E\{\max(\frac{1}{P^{k+1}_{t_{i+1}}},\frac{1}{P^{k+2}_{t_{i+2}}},.....,\frac{1}{P^{Q}_{t_{i+Q-k}}})\}} \tag{8}$$

We will consider the lower bound of (8). Consequently, the aim now is to get $E\{\max(\frac{1}{P^{k+1}_{t_{i+1}}},\frac{1}{P^{k+2}_{t_{i+2}}},.....,\frac{1}{P^{Q}_{t_{i+Q-k}}})\}$. For simplicity, denote it by V^k_i.

According to (5), and extending for k to-be-transmitted packets, $P^k_{t_i} = \frac{C\times k}{|H_i|^2}$, where C is a constant equals to $-ln(2\overline{P_b})\times N_0 \times \frac{R_b(4\pi d)^2}{G_tG_r\lambda^2}M_lN_f$. Similarly, $P^{k+1}_{t_{i+1}} = \frac{C\times(k+1)}{|H_{i+1}|^2}$, and so on for all i and any k. Then,

$$V^k_i = E\{\max(\frac{1}{P^{k+1}_{t_{i+1}}},.....,\frac{1}{P^{Q}_{t_{i+Q-k}}})\} = \frac{1}{C}\times E\{\max(\frac{|H_{i+1}|^2}{k+1},.....,\frac{|H_{i+Q-k}|^2}{Q})\} \tag{9}$$

Since all transmission channels $|H_i|^2$, for all i, are assumed to be Rayleih-fading channels, any $|H|^2$ is exponentially distributed. Rewritting (9):

$$V^k_i = E\{\max(\frac{1}{P^{k+1}_{t_{i+1}}},.....,\frac{1}{P^{Q}_{t_{i+Q-k}}})\} = \frac{1}{C}\times E\{\max(X^{k+1}_{i+1},.....,X^{Q}_{i+Q-k})\} \tag{10}$$

Where X's are set of exponentially random variables. Let $F_X(x)$ be the Cumulative Density Function (CDF) of the variables X^k_i.

$$F_X(x) = 1 - e^{-\lambda x} \tag{11}$$

Let $F_q(v^k_i)$ be the Cumulative Density Function (CDF) of V^k_i. For Independent and Identically Distributed (iid) X's, $F_q(v^k_i)$ is simply given by:

$$F_q(v^k_i) = P[(x^{k+1}_{i+1} < v)\cap(x^{k+2}_{i+2} < v).....\cap(x^{Q}_{i+Q-k} < v)] = \prod_{n=k(i)+1}^{Q}(1-e^{-\lambda_n x}) \tag{12}$$

Where $\lambda_n = n\times\lambda$ with λ the rate of the exponential distribution (assumed to be 1) and $k(i)$ is number of packets kept in the queue at round i.

Then,

$$V^k_i = \int_0^\infty [1 - \prod_{n=k(i)+1}^{Q}(1-e^{-\lambda_n x})]dx = \frac{Q+1-k(i)}{Q+1} \tag{13}$$

Going backward from equations (8) to (6) with the known value of V^k_i, (6) can be rewritten as

$$X_i^{(k)} = \min\{P^k_{t_i}, \frac{1}{C}\times\frac{Q+1-k(i)}{Q+1}\} \tag{14}$$

Clearly from (14), the optimal stopping rule results in a threshold-comparison problem that compares the instantaneous transmission power with the minimum expected transmission power if the packet is kept in the queue. Also, it is clear that the stopping rule takes into consideration how many packets are already existing in the queue, denoted by k, besides the packet that has to be transmitted at this round. For instance, Table 1 shows the values of the thresholds for queue sizes of 3.

Table 1. THRESHOLDS FOR Q=3

Q=**3**	$k(i)=0$	$k(i)=1$	$k(i)=2$	$k(i)=3$
Threshold × C	$\frac{4}{4}=1$	$\frac{4}{3}=1.33$	$\frac{4}{2}=2$	$\frac{4}{1}=4$

Accordingly, for a queue of size Q, thresholds according to kept packets $k = 1, 2, ..., Q$ are given by $\frac{1}{C} \times \{\frac{Q+1}{Q+1}, \frac{Q+1}{Q}, \frac{Q+1}{Q-1}, \frac{Q+1}{Q-2}, \frac{Q+1}{Q-3}, ..., Q+1\}$

2.2 Queue Releasing

In this subsection we intend to optimize the releasing paradigm of the queue. That is, how many packets should be released in any round so as to minimize transmission power. If the number of packets already existing in the queue is k and one packet comes at this round, the node has the option of releasing all of the $k+1$ packets, or releasing k packets and keeping one, or releasing $k-1$ packets and keeping two, and so on till reaching the scenario of releasing no packets and keeping all of the $k+1$ packets. Hence the available scenarios for transmission at round i can be mathematically written as follows:

$(k+1) \times P_{t_i}$
$k \times P_{t_i} + E\{\min(P_{t_{i,1}}, P_{t_{i,2}}, ..., P_{t_{i,Q}})\}$
$(k-1) \times P_{t_i} + E\{\min(P_{t_{i,2}}, P_{t_{i,3}}, ..., P_{t_{i,Q}})\}$
.....
.....
$0 \times P_{t_i} + E\{P_{t_{i,Q}}\}$

Where the second portion in any term of the above represents the expected transmission power if the packet(s) is/are kept till the queue is full. Actually, the second portion can be easily obtained from second portion of (14) for any value of Q and $k(i)$. Accordingly, we formulate an ILP optimization problem to choose the minimum transmission power scenario of all scenarios discussed above.

$$\begin{aligned} \underset{x}{\text{Minimize}} \quad & \sum_{j=0}^{k+1} x_j[(k+1-j)P_{t_i} + E\{\min(P_{t_{i,j}}, P_{t_{i,j+1}}, ..., P_{t_{i,Q}})\}] \\ \text{subject to} \quad & \sum_{j=0}^{k+1} x_j = 1, \\ & x_j = \{0, 1\}, \ \text{for all } j. \end{aligned}$$

Where x represents on-off states that enables only one scenario from the available ones. ILP is NP-complete problem. Hence, there is no known polynomial algorithm which can solve the problem optimally. Optimal solution is still eluding researchers and a huge research effort has been exerted to find optimal solution for such problems either by heuristic algorithms [13,14] or by relaxation of the last constraint ($x_j = \{0,1\},\ \text{for all} j$) [15]. We will follow [15], where the authors proposed a Linear Programming with Sequential Fixing (LPSF) algorithm that relaxes the last constraint. In this case, the formulation becomes a Linear Programming (LP) problem that is solvable in polynomial time. The algorithm is as follows:

i) Relaxing $x_j = \{0,1\},\ \text{for all} j$ to take any continuous value between 0 and 1, and the problem is solved as a LP one. The solution to this LP problem is an upper bound on the optimal solution to our problem.

ii) Among all $x_j,\ \text{for all} j$, the largest one is picked up and denoted, for ease of identification, by x_k. x_k is set to 1. As a result, all x_h for $h \neq k$ is set to 0.

iii) A feasibility check is conducted on the resulting LP problem. An empty feasible region means that the first fixing in this iteration isn't correct. So, x_k is reset to 0 in a new LP and other x_h for $h \neq k$ become variables again.

iv) At this point, either LP problem constructed with $x_k = 1$ or with $x_k = 0$ has a feasible solution.

v) A new iteration starts following the same process above. The process is repeated until all x_j are set to either 0 or 1. We evaluate the performance of our proposed optimal stopping scheme for power minimization by conducting extensive simulation study. Simulations are conducted for a network of 100 nodes, and averaged over 100000 times. We assume channels are constant for one packet transmission. We assume Channel State Information (CSI) of all channels and distances from any node to the destination Base Station (BS) are well known at the BS where the decision is taken. We consider network parameters given in Table 2, in accordance with [4].

Table 2. SIMULATION PARAMETERS

Parameter	**Value**
$G_t G_r$	10 dB
η	0.35
f_c	15 MHz
$\overline{p_b}$	10^{-3}
M_l	10 dB
N_f	10 dB

Fig. 1 shows the amount of saved power through the policy of packet retention. The amount of saving starts with 55% for $Q = 1$ and increases monotonically for larger queue sizes. It is clear that power profile is constant for traditional transmission method (No queue), however through packet retention scheme power decreases as queue size increases. That's because as queue size increases, there are more chances for the nodes to keep the packets in the queue expecting better channel conditions in next rounds.

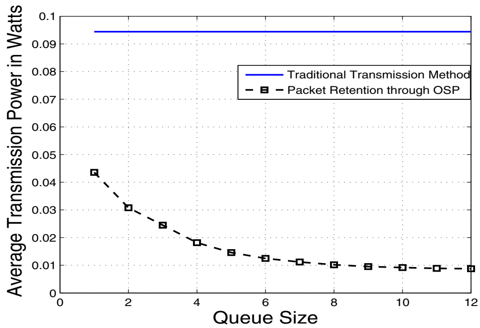

Fig. 1. Power Saving through OSP.

3 Applying OSP to CRSN Under Interference and Delay Constraints

3.1 Problem Formulation and Simulations

In the previous section, we discussed the problem of power minimization in any network through OSP in an interference-free environment. However, inducing the work of OSP to CRSN will have some effects considering transmission power and dropped packets rate. We assume underlay CRSN where SU are transmitting on the same bands licensed for PU as long as strict interference thresholds are well maintained. We formulate a knapsack optimization that chooses the minimum transmission power scenario for the CRSN and takes interference induced to PU into account. As mentioned earlier, we are dealing with delay-tolerant applications; though, we added to this formulation a delay constraint to show its effect. Denoting D_m^k as the delay which packet m undergoes when k packets are in the queue. D_m^k is updated within each round i based on how many rounds packet m has been kept in the queue till releasing. We assume for simplicity one SU interferes with one PU. The interfering channel from the SU to the PU is denoted by h_i^k (The interfering channel at round i when k packet are already in the queue), and it is assumed to be Rayleih-fading channel as well as the transmission channel H mentioned previously. The new problem is formulated as follows:

$$\begin{aligned}
\underset{x}{\text{Minimize}} \quad & \sum_{j=0}^{k+1} x_j[(k+1-j)P_{t_i} + E\{\min(P_{t_{i,j}}, P_{t_{i,j+1}}, \ldots.., P_{t_{i,Q}})\}] \\
\text{subject to} \quad & \sum_{j=0}^{k+1} x_j(k+1-j)P_{t_i} \times |h_i^k|^2 < I \\
& D_m^k \leq D_{max}, \ \text{ for each round } \ i, \\
& \sum_{j=0}^{k+1} x_j = 1, \\
& x_j = \{0,1\}, \ \text{ for all } \ j.
\end{aligned}$$

Where I is a strict interference threshold that must not be exceeded by the SU transmission, and D_{max} is the maximum delay that could be tolerated for each packet m. This problem is a knapsack optimization problem. Knapsack problem is a decision problem that is well known in combinatorial optimization. The knapsack problem is known, as ILP, to be NP-complete. We will use the same algorithm discussed in Sect 2 to solve it. We measure the performance of our scheme in terms of dropped packet rate and power saving. For convenience, a packet is considered dropped if its resulted interference exceeds the interference threshold I. Fig. 2 shows dropped packet rate percentage in case of traditional transmission method as well as transmission through OSP versus various interference threshold. We chose, without loss of generality, $Q = 8$. It is obvious that there is a significant decrease in the dropped packet rate through using OSP than using traditional method. In traditional transmission method, a packet is considered dropped if the resulted interference form its transmission exceeds the interference threshold instantaneously. However through the OSP, it can be kept in the queue expecting better interfering-channel conditions.

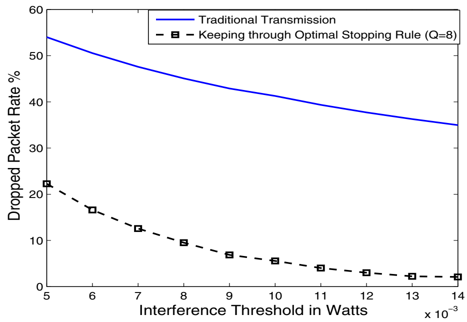

Fig. 2. Dropped Packet Rate in Traditional Transmission Method versus transmission through OSP with Q=8.

There is also an interesting point considering the comparison between traditional transmission method and transmission through OSP. In traditional transmission method, there are more dropped packets, and hence less power is consumed. However, in transmission through OSP, there are less dropped packets and more consumed power. To discriminate one scheme from the other, we consider the term Average Power per Transmitted Packet (APTP) which is defined as average consumed power divided by successfully received packets. APTP is the factor that makes one scheme outperforms the other. As shown in Fig. 3, in both transmission schemes, APTP increases as I increases because less packets are dropped and more power is consumed. However, transmission through OSP outperforms traditional method as it has less consumed power for any I. Traditional transmission method isn't affected by the queue size (Constant curves for the same Q). On the other hand, as Q increases, APTP decreases in transmission through OSP. Improvement in APTP swings from 4% (small Q size (Q=1)) to 23% (large Q size (Q=10)). Improvement for other queue sizes are in-between.

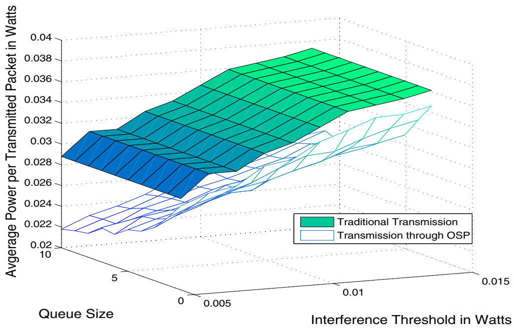

Fig. 3. APTP through traditional transmission method and OSP versus Queue Size and Interference Threshold.

3.2 Effect of Queue Size and Maximum Permissible Delay

As mentioned earlier, our transmission scheme is suitable for delay-tolerant applications such as mine reconnaissance, undersea explorations, environmental monitoring, and ocean sampling. In such applications power saving is an important issue as well as successful packet reception, and end to end delay isn't much important and could be afforded [16]. But, for convenience, we study the effect of both Q and D_{max} simultaneously on the consequent average delay. Fig. 4 shows average consequent delay per packet resulting from transmission through OSP when either one of the parameters Q or D_{max} is fixed, while the

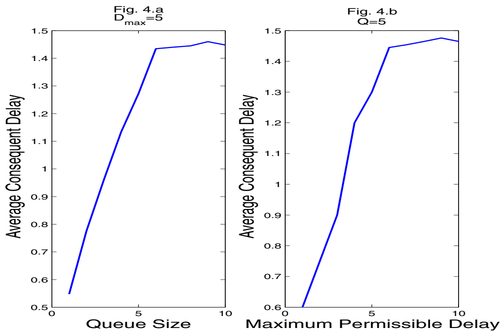

Fig. 4. Effect of Queue Size and Maximum Permissible Delay Parameters on Average Consequent Delay.

other is changing. It is clear that the average consequent delay is dominated by the fixed parameter of both. For instance, in Fig. 4.a, as Q increases, average consequent delay increases till $Q = 5$ which is the value of D_{max}, and then it starts to saturate. The same occurs in Fig. 4.b with fixing Q, and changing D_{max}. This phenomenon happens due to assuming, in our model, that packets are released according to their arrival in a First In First Out (FIFO) fashion. Hence, the smaller parameter dominates the effect on average consequent delay. Consequently, it is better to choose $Q = D_{max}$ to avoid the dominance of one parameter over the other on the average consequent delay.

4 Conclusion

We studied the power minimization problem through OSP fro delay-tolerant applications. Applying optimal stopping theory to packet retention and deriving the optimal stopping rule was the core of the work. We deduced that this transmission scheme outperforms traditional transmission method as far as power minimization is concerned. Also, it was shown that the improvement is overly significant; it reaches 55% for small queue sizes and increases monotonically as queue size increases.

We also extended the work of packet retention through OSP to CRSN where interference threshold to PU must not be exceeded by SU transmissions. Moreover, we studied the effect of queue size as well as the maximum permissible delay for a packet on the average consequent delay. Simulations were conducted in terms of dropped packet rate, APTP, and consequent delay.

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