Prioritized Access in a Channel-Hopping Network with Spectrum Sensing

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***Abstract*—We investigate the performance of priority-based access in a channel-hopping cognitive network, in particular the interaction between the number of packets each node is allowed to send in a single transmission cycle and the penalty coefficient that determines the amount of sensing to be done upon a successful transmission. Our results indicate that giving higher bandwidth allocation to low priority traffic class improves the performance of the network without affecting the performance for high priority class traffic.**

I. Introduction

Priority-based scheduling is often utilized to provide tailored service and improve user satisfaction, and a number of priority-based scheduling schemes have been proposed for various wireless networks [13]. However, priority-based scheduling has received much less attention in the context of cognitive wireless networks, where existing work has mostly focused on interaction with primary users, either through prioritizing channels according to primary user activity [5], or using a combined criterion of historical user Quality of Experience (QoE) data and primary user activity on a given channel [3]. A priority-based virtual queue interface has been used to evaluate the traffic delays and adapt the channel selection strategies accordingly [11]. Also, a dynamic priority management mechanism and associated communication protocols were discussed in the context of a hospital system with dynamic spectrum access (DSA) capable medical, non-medical and sensor devices [1].

In this paper, we consider a channel-hopping cognitive personal area network (CPAN) with transmission tax-based medium access control (MAC) protocol [8] with multiple prioritized traffic classes and investigate its performance. In this protocol, the CPAN hops through available channels in a pseudo-random fashion in order to avoid primary user transmissions, and each of the superframes may take place on a different channel. Transmission tax is the mechanism to ensure accurate information about primary user activity obtained by spectrum sensing. Namely, sensing is performed collaboratively by all nodes in the amount that is proportional to the number of packets transmitted and a penalty coefficient. Sensing results are sent to the CPAN coordinator which uses them to select the next-hop and backup channels [9].

In this setting, priority can be enforced between individual nodes in the CPAN in several ways. First, node transmissions can be scheduled according to their priority, which affects the probability of collision with primary user transmission, as transmissions that take place later in the superframe are more likely to suffer from such collisions. Second, nodes can be prioritized through scheduling policy, i.e., the maximum number of packets which nodes of a given class is allowed to transmit in single access. Finally, nodes of different traffic classes can be assigned different values of the penalty coefficient and, by extension, different amount of sensing. As the result, nodes that perform more sensing will have less chance to transmit which may, in turn, increase access times compared to that of higher priority traffic classes. This effect can be partly compensated for through scheduling policy, but this may affect the overhead imposed by transmission allocation. The investigation of these prioritization mechanisms and their interplay is the topic of this paper. Some of the scheduling mechanisms were analyzed in our earlier work but for a single traffic class only [10], while the work reported here models multi-class access and analyzes impacts of bandwidth allocation per class.

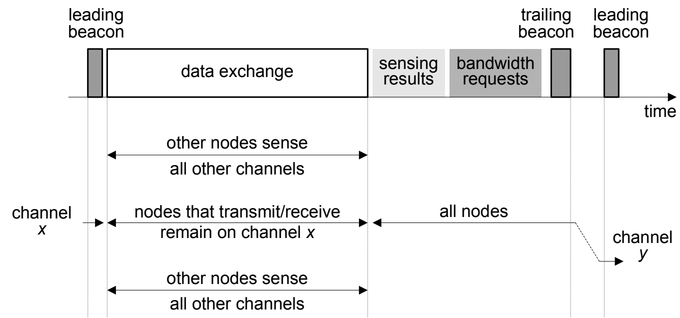

Fig. 1. Superframe format: some nodes transmit and receive data, some have just finished transmitting and undertake sensing, some have been sensing and report back to the CPAN coordinator.

The paper is organized as follows: Section II gives more details about the operation of channel-hopping cognitive network, while Section III models the durations of transmission, sensing and waiting times. Packet access delay is derived in Section IV. Section V presents the performance data and Section VI concludes the paper and highlights some avenues for future research.

II. CPAN operation

A CPAN piconet is comprised of a dedicated coordinator which is responsible for starting the piconet, admitting nodes to join the piconet, monitoring and controlling its operation, and other administrative tasks, and a number of ordinary nodes that exchange data. Nodes belong to one of m priority classes,

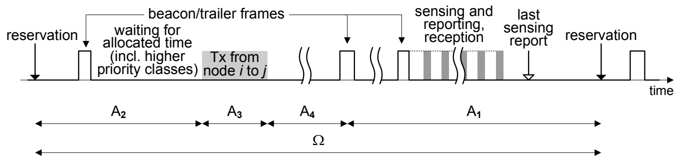

Fig. 2. Distribution of arrivals during service cycle.

with class 1 having the highest priority. Time is partitioned into superframes marked by leading and trailing beacons emitted by the coordinator, as shown in Fig. 1. Each superframe may use a different channel from the working channel set, chosen in a pseudo-random manner from the set of channels which are currently free of primary source activity. Channel information is obtained by collaborative sensing effort of all ordinary nodes and, if needed, the coordinator as well.

A node that has data to transmit requests a suitable time slot (or slots), up to K_i for a node of class $i \leq m$, during the reservation sub-frame. The coordinator services such requests in a round-robin fashion, as described below, and announces the allocations in the next leading beacon. Time allocation for n packet slots includes an obligation to perform sensing during $nk_p^{(i)}$ subsequent superframes, where $nk_p^{(i)}$ is the penalty coefficient for class i. In each superframe, sensing nodes report results to the coordinator and listen to both trailing and subsequent leading beacons: first because they need to know the next-hop and backup channels [9], and second, because they might need to temporarily suspend sensing in order to receive packets. Nodes can apply for bandwidth again only when they finish the sensing duty, but a node that finishes sensing and still has no packets to send will undertake another sensing cycle of the same length as the previous one.

Fig. 2 shows the operation of an arbitrary node. Node transmission time is randomly positioned with respect to the beacon and, by extension, to the control and reservation sub-frames that have fixed duration and immediately precede the beacon. The distance between the end of a transmission and next beacon (which includes control and reservation sub-frames) is referred to as the beacon synchronization time. During the reservation sub-frame, the coordinator receives bandwidth allocation requests and sorts them according to traffic class and node IDs. Allocation includes as many requests as can fit into one superframe; requests that can't be granted in the current superframe are deferred to the next one, which amounts to a gated scheduling policy with vacations [12].

Within a single traffic class, transmission opportunities are given to the nodes in a round robin fashion. Such scheduling policies range from 1-limited, where each node transmits one data packet at a time, through K-limited, where each node transmits up to K packets at a time, to exhaustive, in which a node is allowed to transmit all the packets it has in its buffer. 1-limited scheduling offers fair access and short waiting times under high load, while exhaustive scheduling results in best performance under low load, but introduces unfairness and can even result in starvation [4]. Of course, these results hold in a scenario without the overhead due to sensing and MAC set-up times, which complicate analysis in our case.

III. Model of MAC algorithm with sensing penalty

Assuming that the basic time unit in the network is the sensing slot, the total superframe length is s_f slots while the data packet size is constant and equal to k_d basic sensing slots, with an additional one-slot packet for acknowledgement. Then, the probability generating function (PGF) for the packet size, including acknowledgment, is $b(z) = z^{k_d+1}$. Since the probability distribution of packet time with acknowledgment is discrete, its Laplace-Stieltjes transform (LST) is obtained by substituting variable z with e^{-s}, i.e., $b^*(s) = e^{-s(k_d+1)}$. Packets arrive at the class i node according to a Poisson process with arrival rate λ_i. Offered load at the class i node is $\rho_i = \lambda_i \bar{b}$. We assume that all nodes have buffers of infinite capacity.

Each traffic class i has M_i nodes giving the total of $M = \sum_{i=1}^{m} M_i$. Traffic from higher priority nodes is scheduled before that from lower priority nodes, with highest priority packets transmitted immediately after the leading beacon. When all the nodes from highest priority have been served, coordinator schedules next lower priority class and so on until all nodes have been served. Nodes within any given priority class are scheduled in a round robin fashion, in the order derived from node IDs.

Each node is granted transmission for the packets that have arrived up to the moment when the node applies for transmission; packets that arrive afterwards must wait for the packet transmission and subsequent sensing periods before the next bandwidth request. This includes periods of waiting for transmission, sensing and synchronization with the beacon, as shown in Fig. 2.

To derive the balance equation for the node queue at the moments of return from sensing under K-limited service, we need to characterize different periods defined in the MAC protocol. Table I lists probability density functions (pdf's) and PGFs of the arrival processes for those periods.

If each node of class i is allowed to transmit up to K_i packets in each transmission cycle, balance equations for each traffic class are

$$
\begin{aligned}
q_k^{(i)} &= q_0^{(i)} a_{1,k}^{(i)} + \sum_{j=1}^{K_i-1} q_j^{(i)} \cdot \\
&\int_{x=0}^{\infty} \frac{(\lambda_i x)^k}{k!} e^{-\lambda_i x} d_2^{(i)}(x) * b(x)^{(j)} * v_u(x)^{(j)} * d_4(x) dx \\
&+ \sum_{j=K_i}^{\infty} q_j^{(i)} \int_{x=0}^{\infty} \frac{(\lambda_i x)^{k-j+K_i}}{(k-j+K_i)!} e^{-\lambda_i x} \cdot \\
&d_2^{(i)}(x) * b(x)^{(K_i)} * v_u(x)^{(K_i)} * d_4(x) dx \qquad (1)
\end{aligned}
$$

where $q_j^{(i)}$ denotes mass probability of having j packets upon return from sensing for a node in traffic class i; symbol $*$ denotes convolution; $b(x)^{(j)}$ denotes j-fold convolution of packet

TABLE I
FOR PERIODS AND PGFS FOR ARRIVAL PROCESSES WITHIN MAC

period	period pdf	arrival process PGF	mass probabilities for arrival PGF
waiting for allocated time (includes busy periods of higher priority classes)	$d_2(x)$	$A_2^{(i)}(z)$	$a_{2,k}^{(i)}$
data transfer for target node	$s(x)$	$A_3^{(i)}(z)$	$a_{3,k}^{(i)}$
sensing period as penalty for single transmitted packet	$v_u(x)$	$A_f^{(i)}(z)$	$a_{f,k}^{(i)}$
total sensing period	$v(x)$	$A_1^{(i)}(z)$	$a_{1,k}^{(i)}$
sensing for a single superframe	$\frac{1}{s_f}$	$A_0^{(i)}(z)$	$a_{0,k}^{(i)}$
synchronization with the beacon	$d_4(x)$	$A_4^{(i)}(z)$	$a_{4,k}^{(i)}$
single packet transmission	$b(x)$	$A_s^{(i)}(z)$	$a_{s,k}^{(i)}$

transmission time; and $v_u(x)^{(j)}$ denotes j-fold convolution of single packet penalty time.

Probability generating function (PGF) for the number of packets queued at node from class i is $Q^{(i)}(z) = \sum_{j=0}^{\infty} q_j^{(i)} z^j$; it can be obtained by multiplying left- and right-hand sides of (1) and summing them from 0 to ∞, followed by exchanging integration and summation, and reversing the order of summations in nested sums. The resulting PGFs are rational functions of the form $Q^{(i)}(z) = \frac{Qn^{(i)}(z)}{Qd^{(i)}(z)}$. For tractability, we also need auxiliary PGFs, the sequence of arrival PGFs as $\beta_j^{(i)}(z) = A_2^{(i)}(z)A_4^{(i)}(z)(A_s^{(i)}(z)A_f^{(i)}(z))^j, j = 1 \,..\, K_i$ and partial PGF of $Q_{kl}^{(i)}(z) = \sum_{j=1}^{K_i-1} q_j^{(i)} z^j$. These two are then used to write denominator and numerator polynomials as

$$Qn^{(i)}(z) = z^{K_i} q_0^{(i)} A_1^{(i)}(z) + z^{K_i} \sum_{j=1}^{K_i-1} q_j^{(i)} \beta_j^{(i)}(z) - \beta_{K_i}^{(i)}(z) Q_{kl}^{(i)}(z) \quad (2)$$

$$Qd^{(i)}(z) = z^{K_i} - \beta_{K_i}^{(i)}(z) \quad (3)$$

From the condition $Q^{(i)}(1) = 1$, we can find the probability $q_0^{(i)} = \frac{q_n}{q_d}$, where

$$q_n = K_i - \beta_{K_i}^{'(i)}(1) - \sum_{j=1}^{K_i-1} \beta_j^{'(i)}(1) + Q_{kl}^{'(i)}(1) + Q_{kl}^{(i)}(1)\beta_{K_i}^{'(i)}(1)$$
$$q_d = K_i + A_1^{'(i)}(1) \quad (4)$$

with $\beta_j^{'(i)}(1) = \overline{\beta_j^{(i)}}$; similar derivations hold for $A_1^{'(i)}(1)$ and $Q_{kl}^{'(i)}(1)$.

Mass probabilities $q_k^{(i)}$, $k = 1 \,..\, K_{max}$ (where K_{max} depends on the tradeoff between accuracy and computational complexity) can be found as follows. Let us observe that each $Q^{(i)}(z) = \frac{Qn^{(i)}(z)}{Qd^{(i)}(z)}$ must be bounded in the range $z = [0 \,..\, 1]$. Therefore, (complex) zeros of the denominator must be the zeros of the numerator as well. This condition generates $K_i - 1$ equations in unknowns $q_k^{(i)}$. The remaining equations can be found by extracting and equating polynomial coefficients of degrees $K_i \,..\, K_{max}$ from the series equation $\sum_{k=0}^{K_{max}} q_k^{(i)} z^k Qd^{(i)}(z) = Qn^{(i)}(z)$. Once we add the normalization equation, the system can be solved. However, PGF-s $\beta_{K_i}^{(i)}(z)$ require probability distributions of the number of packet arrivals during specific periods related to MAC definitions and we will derive them in the text that follows. Once $Q^{(i)}(z)$ is known, other performance descriptors can be derived as well.

A. Modeling important periods and arrival PGFs

When a node is granted access in the current superframe, the PGF for the number of transmitted packets is

$$\Phi^{(i)}(z) = \frac{\sum_{k=1}^{K_i-1} q_k^{(i)} z^k + \sum_{k=K_i}^{\infty} q_k^{(i)} z^{K_i}}{1 - q_0^{(i)}} \quad (5)$$

The duration of this period is $\Phi^{(i)}(b(z))$ with the mean value $\overline{\Phi^{(i)}} \cdot \overline{b}$. If we consider superframes when the node buffer is empty (which results in a service period of zero length), the PGF for the service period is

$$Sr^{(i)}(z) = \sum_{k=0}^{K_i-1} q_k^{(i)} z^k + \sum_{k=K_i}^{\infty} q_k^{(i)} z^{K_i} \quad (6)$$

The PGF for the number of packets that arrive to the node during transmission time is

$$A_3^{(i)}(z) = \Phi^{(i)*}(\lambda_i - \lambda_i z). \quad (7)$$

Since the duration of sensing duty is proportional to the number of transmitted packets, its probability distribution can be derived from the distribution of the length of the busy period, and its PGF is

$$V^{(i)}(z) = \frac{\sum_{k=1}^{K_i-1} q_k^{(i)} z^{k k_p^{(i)} s_f} + \sum_{k=K_i}^{\infty} q_k^{(i)} z^{K_i k_p^{(i)} s_f}}{1 - q_0^{(i)}} = \Phi^{(i)}(z^{k_p^{(i)} s_f}) \quad (8)$$

The number of packet arrivals to the node during a single vacation period has the PGF of

$$A_1^{(i)}(z) = V^{(i)*}(\lambda_i - \lambda_i z) = \sum_{k=0}^{\infty} a_{1,k}^{(i)} z^k \quad (9)$$

After packet transmission, the node needs to wait for the next trailing beacon in order to learn about the next and backup channels. This waiting time is residual time with respect to a random point in superframe, and its LST has the form $R^*_-(s) = (1 - e^{-s \cdot s_f})/(s s_f)$; the corresponding number of packet arrivals has the PGF of $A_4^{(i)}(z) = R^*_-(\lambda_i - \lambda_i z)$.

A class i node has to wait until all nodes from higher priority classes as well as all nodes from that same class, but with IDs lower than its own that have packets have been served. Assuming the CPAN has $M = \sum_{i=1}^{m} M_i$ nodes, the class i cycle time can be defined as the time between two successive transmission opportunities for the node, with the LST of

$$C^{(i)*}(s) = \prod_{j=1}^{i-1} C^{(j)*}(s) (Sr^{(i)*}(s))^{M_i} \tag{10}$$

After applying for bandwidth node from class i has to wait for full cycles of higher priority traffic and all nodes from the same class which have smaller IDs. As a random number of class i nodes participate in each cycle under Poisson arrivals and node ID is randomly positioned with respect to IDs of nodes served in the cycle, the latter time can be characterized as elapsed cycle time [2], and it can be obtained as

$$C_-^{(i)*}(s) = \frac{1 - C^{(i)*}(s)}{s\overline{C^{(i)}}} \tag{11}$$

The number of packet arrivals during the time spent waiting for the round-robin service has the PGF of

$$A_2^{(i)}(z) = \prod_{j=1}^{i-1} C^{(j)*}(\lambda_i - \lambda_i z) C_-^{(i)*}(\lambda_i - \lambda_i z). \tag{12}$$

B. Probability of collision with primary source

An important aspect of priority scheduling in cognitive networks is the probability of collisions with primary user transmissions. To evaluate this effect, we assume that CPAN hops over N channels, each of which may be occupied by an independent primary source. Active and idle times of primary sources are random variables with pdf's $t_{on}(x)$ and t_{off} and mean durations of $\overline{T_{on}}$ and $\overline{T_{off}}$, respectively. Cycle time is $\overline{T_{cyc}} = \overline{T_{on}} + \overline{T_{off}}$. Probability density function (pdf) for the channel residual idle time is proportional to the probability that idle time is larger than some value y scaled to the mean idle time $d(y) = \frac{\int_{z=y}^{\infty} t_{off}(z)dz}{\overline{T_{off}}}$ [2].

One type of collisions occurs when the primary source begins transmitting during a transmission of the node from traffic class i. As higher traffic classes are scheduled to transmit sooner after the beacon, they will experience fewer collisions compared to the lower priority classes. Since the arrival of the CPAN to the idle channel is a random point in idle channel time, collision probability for traffic class i can be calculated as the probability that residual idle channel time is shorter than superframe duration:

$$P_c^{(i)} = \int_{x=0}^{\infty} (D(x + \sum_{j=1}^{i} \overline{C^{(j)}} + \overline{C_-^{(i)}} + \overline{S^{(i)}}) - D(x)) d(x) dx \tag{13}$$

where $D(x) = \int_0^x d(y)dy$.

Another type of collisions is caused by errors in the coordinator's channel table: as the primary source may begin transmitting after a sensing event, the next-hop channel may be unusable. Errors of this type affect all traffic classes in the same way. Probability that a node from traffic class i will be active in spectrum sensing is

$$P^{(i)} = \frac{\overline{I^{(i)}}}{\overline{S^{(i)}} + \sum_{j=0}^{i-1} \overline{C^{(j)}} + \overline{R_-^{(i)}} + \overline{C_-^{(i)}} + \overline{I^{(i)}}} \tag{14}$$

Then, probability distribution for the number of nodes simultaneously involved in sensing is

$$\Xi(z) = \prod_{i=1}^{m} \sum_{j=0}^{M_i} \binom{M_i}{j} (P^{(i)})^j (1 - P^{(i)})^{M_i - j} z^j \tag{15}$$

which can be presented as the series $\Xi(z) = \sum_{n=0}^{M} \xi_n z^n$, where ξ_n denotes mass probability that n nodes are involved in spectrum sensing. (Coordinator can also perform spectrum sensing if necessary, in particular when there are no ordinary nodes available.) We also assume that node performs sensing in d time slots and chooses next channel randomly over all channels except the current one with probability $P_n = \frac{1}{N-1}$. Under these assumptions and considering expression (15), probability distribution of the time period between two consecutive sensing events on the same channel has the PGF of

$$\begin{aligned} H(z) = \xi_0 \sum_{k=1}^{\infty} P_n (1 - P_n)^{k-1} z^k d + \sum_{\min(M,N-2)+1}^{M} z^d \\ + \sum_{l=1}^{\min(M,N-2)} \xi_l \sum_{k=1}^{\infty} l P_n (1 - l P_n)^{k-1} z^k d \end{aligned} \tag{16}$$

This result allows us to obtain the probability p_s of having inaccurate channel state in the channel table, following the steps outlined in [7]. Note that p_s is common to all traffic classes, even though they contribute to the sensing process by different amounts.

Total collision probability is, then, $P_{Col}^{(i)} = P_c^{(i)} + p_s$.

IV. Packet access delay

Transmission from a class i node includes up to K_i packets that were in its buffer upon application for bandwidth will be serviced. (Packets that arrived after the bandwidth request will be serviced in the next cycle.) The number of packets left in the buffer of a class i node after n-th departing packet depends on the queue state at the moment of bandwidth request and on any additional packet arrivals before the actual service:

$$L_n^{(i)}(z) = \frac{A_2^{(i)}(z) A_s^{(i)}(z)^n \sum_{k=n}^{\infty} q_k^{(i)} z^k}{z^n \sum_{k=n}^{\infty} q_k^{(i)}} \tag{17}$$

where $0 < n \leq K_i$. We can further derive the PGF for the number of packets left after any departing packet as

$$L^{(i)}(z) = \frac{A_s^{(i)}(z)A_2^{(i)}(z)}{\overline{\Phi^{(i)}}} \Big[Q_{kl}^{(i)}(A_s^{(i)}(z)) - Q^{(i)}(z) - (\frac{A_s^{(i)}(z)}{z})^{K_i}(Q^{(i)}(z) - Q_{kl}^{(i)}(z))\Big] \quad (18)$$

Probability distribution of access time for a class i node can be found from the observation that the number of packets left after the departing packet is equal to the number of packets that have arrived to the queue while the target packet was in the system, $L^{(i)}(z) = T^{(i)*}(\lambda_i - \lambda_i z)$. By using the substitution $s = \lambda_i - \lambda_i z$, we derive the LST of the packet access time as $T^{(i)*}(s) = L^{(i)}(1 - \frac{s}{\lambda_i})$.

V. Performance evaluation

We have considered the CPAN with two traffic classes with $M_1 = M_2 = 5$ nodes each, for different combinations of scheduling parameter K_i. Packet arrival rate for both traffic classes was varied between $\lambda_1 = \lambda_2 = 0.001$ and 0.003. Penalty coefficient for the traffic class 1 was set to $k_p^{(1)} = 0.25$, while that for lower priority class 2 was varied in the range $k_p^{(2)} = 0.25 \, .. \, 1$. Packet duration time was set to $k_d = 10$ time units, acknowledgment duration to one basic slot, and the superframe duration to $s_f = 100$ basic slots. CPAN uses $N = 30$ channels, each of which is occupied by an independent primary source with exponentially distributed ON and OFF periods with mean values of 900 and 2100 slots, respectively, resulting in mean cycle time of $T_{cyc} = 3000$ basic slots with activity factor of $p_{on} = 0.3$. We have solved the system of equations using Maple 13 by Maplesoft, Inc. [6].

Fig. 3 shows the impact of scheduling parameter on the performance of traffic class 1, with diamonds, boxes, circles, and crosses corresponding to $K_1 = 1$, 2, 3, and 4, respectively. A slight increase of access time (around 20%) may be observed with increasing K_1 but this is still well below the stability limit. Numbers of packets served in a transmission cycle are very similar for $K_1 = 2$ and up, and only several percent larger than for $K_1 = 1$. By the same token, collision probability is almost the same for $K_1 = 2, 3, 4$, and only about 4% smaller when $K_1 = 1$. Mild difference of performance parameters is a consequence of moderate traffic load for traffic class 1. We may thus conclude that increasing the scheduling parameter K_1 above 2, where performance is very good, shows no significant improvement for class 1 traffic. Higher values of K_1 might be considered only when traffic load increases, or higher sensing penalty is required due to the high number of channels.

In that same experiment, we have also varied the scheduling parameter K_2 from 2 to 4, but without any noticeable impact on the performance of traffic class 1, which is why these diagrams are not shown.

In the second experiment, we have assigned same value of scheduling parameter $K_1 = K_2 = 2$ to 4; the results are shown in Fig. 4 for class 2 traffic. Unlike class 1 traffic, the value of the penalty parameter is important for the performance: when $k_p < 1$, scheduling parameter K_2 can be set to two and the CPAN operates smoothly. However, for $k_p = 1$ and $K_2 = 2$, the CPAN approaches stability limit marked by large access time. When K_2 is increased to 3, access time has a large drop of about 40%, and further increase of scheduling parameter gives no improvement. Performance of class 2 traffic with $K_2 = 4$ is similar, with a slight increase in transmission cycle time, collision probability and access time due to the larger number of packets served in a single transmission cycle. Overall, we find that access time has a mild minimum for $K_2 = 3$. At the same time, performance of class 1 traffic was not affected.

VI. Conclusion

We have modeled and evaluated tradeoff of prioritized and fair access in cognitive CPAN with multiple traffic classes. We used class ordering and duration of sensing for priority differentiation and K-limited scheduling per class as a fairness mitigation parameter. Our results show that larger scheduling parameters for low traffic classes do not affect higher traffic classes. On the other hand they extend stability region of lower class nodes and still ensure accurate spectrum sensing reports.

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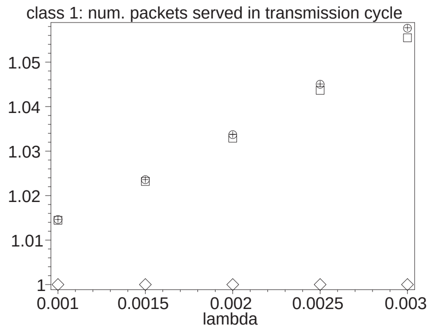
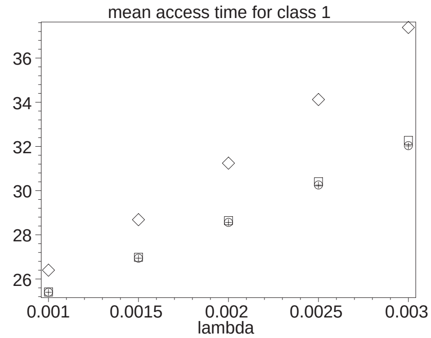
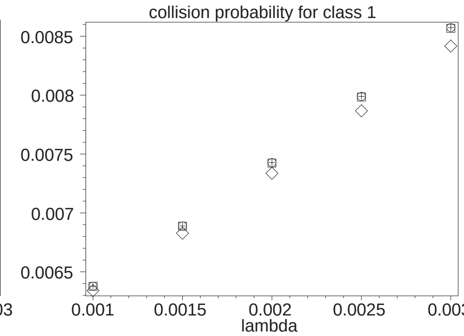


(a) Mean number of packets per node served in one active transmission cycle.

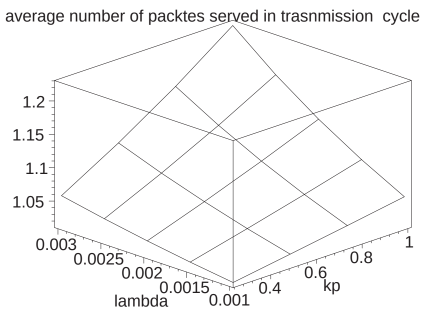


(b) Mean packet access time.

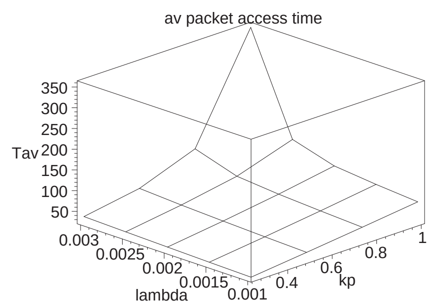


(c) Probability of collision with the primary user transmission.

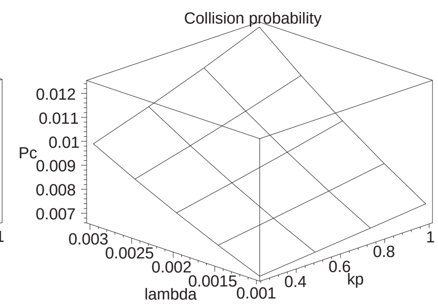
Fig. 3. Performance of class 1 traffic.



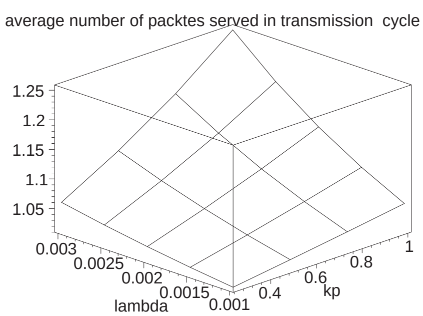
(a) Mean number of packets per node served in one active transmission cycle, $K_1 = K_2 = 2$.



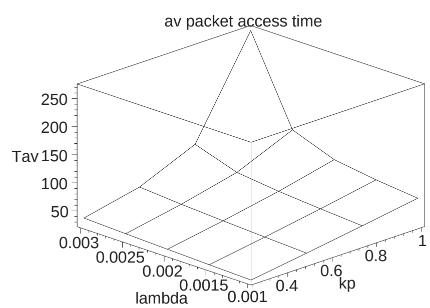
(b) Mean packet access time, $K_1 = K_2 = 2$.



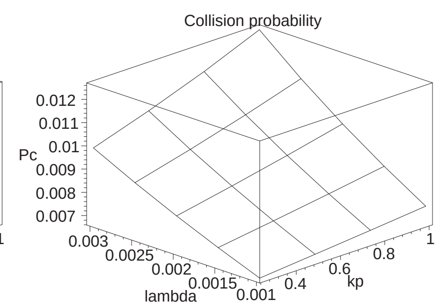
(c) Probability of collision with the primary source, $K_1 = K_2 = 2$.



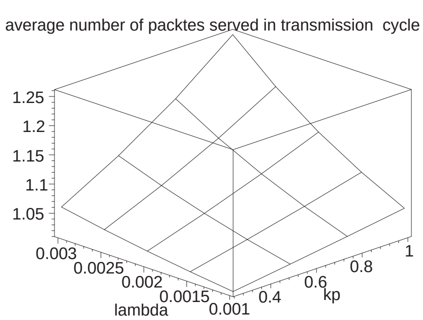
(d) Mean number of packets per node served in one active transmission cycle, $K_1 = K_2 = 23$.



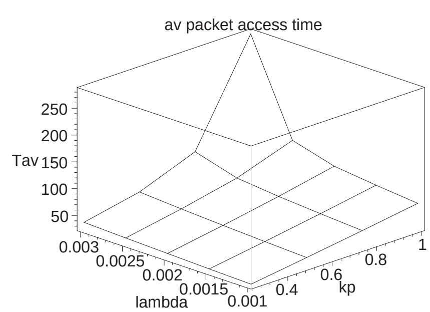
(e) Mean packet access time, $K_1 = K_2 = 3$.



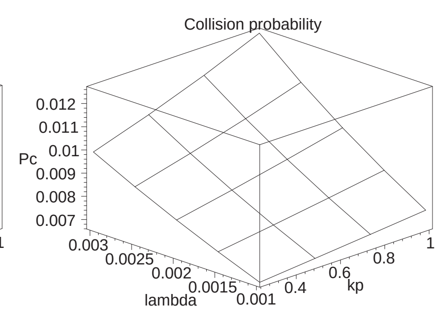
(f) Probability of collision with the primary source, $K_1 = K_2 = 3$.



(g) Mean number of packets per node served in one active transmission cycle, $K_1 = K_2 = 4$.



(h) Mean packet access time, $K_1 = K_2 = 4$.



(i) Probability of collision with the primary source, $K_1 = K_2 = 4$.

Fig. 4. Performance of class 2 traffic.