Simple and Efficient MAC for Cognitive Wireless Personal Area Networks

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Abstract—In this paper we investigate the performance of a cognitive personal area network (CPAN) with round robin service where each node is allowed to transmit at most one packet in one transmission cycle. Furthermore, upon transmitting a packet, the node has to perform spectrum sensing in order to distribute the sensing load in a fair manner and enable smooth operation of the CPAN. Duration of the sensing period is regulated by a predefined penalty coefficient; however, sensing may be interrupted by reception activity of the node. We present a probabilistic model of this system and investigate the performance limits with respect to the traffic load and value of the penalty coefficient.

I. INTRODUCTION

The novel communications paradigm of cognitive or opportunistic spectrum access (OSA) allows efficient use of existing wireless spectrum opportunities [1], [3]. When combined with frequency hopping spread spectrum (FHSS), OSA technology may be applied in wireless personal area networks in order to increase their resilience to interference from primary users’ activity [6]. Efficient operation of a frequency-hopping cognitive personal area network (CPAN) thus necessitates accurate and timely sensing of all working channels in the chosen band. A dedicated CPAN coordinator collects and combines sensing results to obtain a coherent map of busy and idle channels [10], which is subsequently used to create an adaptive hopping sequence for the entire CPAN.

Another task of the coordinator is to ensure fairness among nodes, which means not only equal opportunities for transmission, but also equal contribution to smooth operation of the CPAN through sensing. Furthermore, an effective balance between transmission and sensing must be achieved and maintained, which necessitates a flexible transmission scheduling protocol.

In this paper, we propose a simple protocol that ensures fairness in transmission as well as in sensing, and present a detailed performance analysis of data transmission in such a CPAN. In this protocol, nodes are granted bandwidth to transmit only one packet each in one transmission cycle, on a round-robin basis. Upon transmission, each node is required to devote a certain amount of work to sensing, in the form of a post-payment or penalty for transmission services rendered by the CPAN. This will obviously affect the traffic performance in the CPAN. Reception is not penalized since the penalty is already born by the transmitter, hence it does not affect the CPAN performance.

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

II. THE SENSING-AFTER-TRANSMISSION POLICY

A CPAN piconet consists of a dedicated coordinator and a number of nodes. The coordinator is responsible for starting the piconet, admitting nodes to join the piconet, monitoring and controlling its operation, and for other administrative tasks. Time is partitioned into superframes of fixed size, similar to other recent communication technologies such as IEEE 802.15.3 [5]. Each superframe is marked by a beacon frame emitted by the coordinator, as shown in Fig. 1. Each superframe uses a different channel from the working channel set, and the hopping sequence is random as well as adaptive, in the sense that the next working channel is chosen in a pseudo-random manner from the set of channels which are currently free of primary source activity.

Activities such as node association and disassociation, bandwidth allocation requests and announcements, sensing allocation and reporting, and actual data transfers, take part in dedicated sub-frames within the superframe, as shown in Fig. 1. A device that wants to transmit a data packet to another device requests a suitable time slot during the reservation sub-frame. During the reservation sub-frame, the coordinator receives bandwidth allocation requests and grants them in round-robin fashion. (A simple way to achieve this is to sort all pending requests according to source address, and allocate bandwidth starting from the last serviced node.)

The policy in which nodes are served in a round-robin fashion and allowed to transmit at most one packet at a time is known as one-limited [7], [9]; it ensures both short- and long term fairness among the nodes.

Allocation includes as many requests as can fit into one superframe, given that each node is granted transmission of at most one packet; requests that can’t fit in the current superframe are deferred to the next one(s). Appropriate announcements are made during the assignment sub-frame which immediately follows the beacon.

Upon transmitting the packet, the node has to perform sensing duty for \( k_p \) subsequent superframes, where \( k_p \) is the penalty coefficient, before requesting to transmit another packet. When \( k_p < 1 \), spectrum sensing will be done for a single superframe after every \( 1/k_p \) transmissions. In this
manner, each node given bandwidth to transmit actually pays for it by spending some time in sensing.

Upon sensing, nodes send the results back to the coordinator during the control sub-frame of the current superframe, and listen to the beacon of the next superframe and subsequent assignment sub-frame.

If a node that is currently sensing learns from the beacon that it is to receive a packet, it suspends sensing during that superframe, receives the packet, and resumes sensing after the next beacon frame. (Suspension may again be needed if another packet is to be received.) Transmission need not be suspended because of reception, as the node only has to switch its radio from one mode to another within the same superframe.

Packets that arrive during the transmission of an earlier packet and/or sensing are queued in the node buffer but not transmitted. Bandwidth requests are prohibited until the node has spent at least \( k_p \) superframes in sensing. (Sensing duty is thus discharged at the expense of extending the packet service cycle.) Once the sensing is done, the node may immediately apply for bandwidth allocation in the next reservation sub-frame – if there are packets queued for transmission, otherwise another sensing cycle of the same length as the previous one is immediately launched; this would effectively extend the penalty coefficient \( k_p \).

III. MODELING THE SENSING-AFTER-TRANSMISSION POLICY

The timing diagram showing the operation of a target node, say, \( i \), is shown in Fig. 2. Time interval between the end of a transmission and the next beacon (which includes control and reservation sub-frames) is referred to as the beacon synchronization time. Note that packet transmission time is randomly positioned with respect to the beacon and, by extension, to the control and reservation sub-frames that immediately precede the beacon.

The packet service cycle \( Y \), from the moment the node applies for bandwidth to the end of the sensing duty, consists of the following components:

1) waiting for the beginning of round-robin packet service,
2) packet service time (packet reception may occur in the same superframe),
3) waiting for the next beacon,
4) spectrum sensing time,
5) (possibly) interrupted by reception of a packet (or packets) from other node(s).

From the aspect of queueing theory, interaction between transmission and sensing can be modeled as 1-limited M/G/1 system with vacations. In this model, packet transmission corresponds to the service period, while the sensing period, waiting for the transmission after requesting bandwidth from the coordinator, synchronization with the beacon, and potential reception of packet, comprise the total vacation period.

Vacation time from the viewpoint of a node consists of the waiting time for service, waiting time for synchronization with the beacon, and spectrum sensing time. Let us now address each of these components in turn, after we define our basic assumptions as follows.

Basic time unit in the system is one sensing slot. Total superframe length is \( s_f \) basic slots. For simplicity, we assume that packet size is constant and equal to \( k_d \) basic sensing slots. Every data packet will be acknowledged immediately after the transmission. Let the probability generating function (PGF) for the packet size with fixed size acknowledgement be \( b(z) = z^{k_d+1} \) with a mean value of \( \bar{b} = k_d + 1 \). Laplace-Stieltjes transform (LST) of the packet time with acknowledgement is obtained by substituting variable \( z \) with \( e^{-s} \), i.e., \( b^*(s) = e^{-s(k_d+1)} \). Packets arrive to the node according to a Poisson process with arrival rate \( \lambda \). Offered load to the node transmission interface is then \( \rho = \lambda Y \). Nodes are assumed to have buffers of infinite capacity.
A. Vacation due to sensing activity

The time spent in sensing is proportional to the number of packets transmitted during the busy period, hence the corresponding PGF is \( V(z) = z^{k_p s_f} \) with mean value of \( \overline{V} = k_p s_f \), while the LST of a single vacation (sensing) period is \( V^*(s) = e^{-k_p s_f s} \). The number of packet arrivals to the node during a single vacation period has the PGF of [9]:

\[
\alpha_1(z) = V^*(\lambda - \lambda z) = \sum_{k=0}^{\infty} f_k z^k, \tag{1}
\]

and the probability of zero packet arrivals is \( f_0 = V^*(\lambda) \), in which case a new sensing period (i.e., vacation) of the same duration begins immediately after the current one.

B. Vacation due to waiting for round robin service

Under the round-robin policy, a node has to wait until all nodes with addresses lower than its own that have packets have been served. Assuming the CPAN has \( M \) nodes, the LST for the cycle time is

\[
C^*(s) = ((1 - \rho) + \rho S^*(s))^M \tag{2}
\]

where \( S^*(s) \) was defined in (5). Mean duration of the CPAN cycle is \( \overline{C} = -C^*(0) = -\frac{dC^*(s)}{ds}\bigg|_{s=0} = \rho M \overline{S} \).

In terms of renewal theory [4], the time between the request for bandwidth allocation and beginning of the service within the cycle is denoted as ‘elapsed’ or backward recurrence time in the discrete time renewal process, where the distribution of the renewal interval is given with the cycle time \( C \). Namely, the target node observes the cycle which starts with the node being served immediately after the beacon in the frame following its request for the bandwidth. Backward recurrence time will be denoted as \( C^- \) and its LST is

\[
C^*(s) = \frac{1 - C^*(s)}{s\overline{C}}, \tag{3}
\]

Its mean value is \( \overline{C^-} = \frac{C^{(2)} - C^{(2)}(0)}{2C} \), where \( C^{(2)} = C^{**}(0) = \frac{d^2 C^*(s)}{ds^2}\bigg|_{s=0} \) denotes the second moment of the cycle time.

The number of packet arrivals during the wait for round-robin service has the PGF of \( \alpha_2(z) = C^*(\lambda - \lambda z) \).

C. Duration of service period

Since only one packet can be transmitted in each service cycle, the PGF for the service time is

\[
S(z) = b(z). \tag{4}
\]

The Laplace-Stieltjes transform (LST) of the duration of node service period is

\[
S^*(s) = b(e^{-s}) = b^*(s) \tag{5}
\]

and its mean value is \( \overline{S} = \overline{b} \). The number of packets that arrive to the node during transmission time has the PGF of \( \alpha_3(z) = S^*(\lambda - \lambda z) \).

D. Vacation due to beacon synchronization

After packet transmission, the node needs to wait for the next control sub-frame in order to report sensing results to the coordinator (see Fig. 1). This waiting time presents ‘residual’ or forward recurrence time in the renewal period presented with superframe duration. Its LST has the form \( R^*(s) = (1 - e^{-s \overline{f}})/s\overline{f} \), and the number of packet arrivals to the node buffer during that time has the PGF of \( \alpha_4(z) = R^*(\lambda - \lambda z) \).

E. Effect of packet reception

In order to model this effect, we need to find the probability distribution of the time interval between transmission and reception by the given node. We will look at the piconet cycle started by the transmission by the target node \( i \in 1 \ldots M \), where \( M \) is the number of nodes in the piconet. Reception by the target node will be triggered by some other node \( j \),

\[Fig. 2. Distribution of arrivals during a service cycle for a single node.\]

\[\begin{align*}
\text{case without the preemption of sensing process.} \\
\text{case with the preemption of sensing process.}
\end{align*}\]
where \( i + 1 \leq j \leq (i + M - 1) \mod M \); we assume that node addresses are uniformly located in that range.

Given that packet size is \( k_d \) slots and one slot is needed for acknowledgement, the PGF for the number of slots between transmission and reception by the node \( i \) is

\[
\Theta(z) = \sum_{k=1}^{M-1} \frac{((1-\rho) + \rho S(z))^k}{M-1} = \sum_{i=1}^{(M-1)(k_d+1)} \theta_i z^i. \tag{6}
\]

Probability that the node will transmit and receive the packet in the same superframe is

\[
P_\theta = P(\Theta < s_f - \Delta) = \sum_{i=1}^{s_f - \Delta} \theta_i, \tag{7}
\]
where \( \Delta \) represents the portion of the superframe dedicated to the reporting of sensing results and bandwidth reservation. The complementary probability that transmission and reception will occur in separate superframes (i.e., that sensing action will be preempted by a superframe in which reception is performed) is \( 1 - P_\theta \). The PGF for the number of packets that arrive during the superframe in which the node is engaged in reception is

\[
o_5(z) = e^{-s_f(\lambda - \lambda z)}. \tag{8}
\]

### F. Packet service cycle time

Packet service cycle begins when the node applies for bandwidth, and ends when the node returns from subsequent sensing. (For simplicity, we assume that the start of a packet service cycle coincides with the leading edge of the beacon, although in reality this happens a bit earlier.) Each packet needs a total service time expressed by the LST

\[
Y^*(s) = S^*(s)C^*(s)R^*(s) (P_\theta + (1 - P_\theta)e^{-s_f}) V^*(s) \tag{9}
\]
with average value

\[
\overline{Y} = \overline{S} + \overline{C} - \overline{R} + (1 - P_\theta)s_f + \overline{V}. \tag{10}
\]

Offered load then becomes \( \rho = \lambda \overline{Y} \). As both cycle time and probability of reception in the same superframe are functions of offered load, expression (10) may be solved for \( \rho \).

Let us denote the PGF for the number of packet arrivals during the packet service cycle as

\[
A(z) = Y^*(\lambda - \lambda z) = \alpha_1(z)\alpha_2(z)\alpha_3(z)\alpha_4(z) (P_\theta + (1 - P_\theta)\alpha_5(z)). \tag{11}
\]

### IV. PACKET ACCESS DELAY

Let us consider the length of the packet queue at the moments of end of packet service cycle and at the end of the node’s vacation. The probability that there are \( k \) packets in the queue after the packet service cycle is denoted as \( \pi_k \) and the PGF for the queue length after the packet service cycle is \( \Pi(z) = \sum_{k=0}^{\infty} \pi_k z^k \). Probability that there are \( k \) packets in the queue at the end of a single vacation is denoted as \( q_k \), and the PGF for the queue length after the sensing period is \( Q(z) = \sum_{k=0}^{\infty} q_k z^k \).

The state transition equations for these two kinds of Markov points are

\[
q_k = (q_0 + \pi_0)f_k \quad k \geq 0
\]

\[
\pi_k = \sum_{j=1}^{\infty} \pi_j \alpha_{k-j+1} \quad k \geq 0 \tag{12}
\]

\[
1 = \sum_{k=0}^{\infty} q_k + \sum_{k=0}^{\infty} \pi_k
\]

In order to obtain the GF’s \( \Pi(z) \) and \( Q(z) \), we multiply expressions (12) and (12) with \( z^k \) and sum over \( k = 1 \ldots \infty \). Then, in terms of probability generating functions, the previous system of equations can be written as

\[
Q(z) = (q_0 + \pi_0)V^*(\lambda - \lambda z)
\]

\[
\Pi(z) = (Q(z) + \Pi(z) - (q_0 + \pi_0)) \frac{Y^*(\lambda - \lambda z)}{z} \tag{13}
\]

\[
1 = Q(1) + \Pi(1)
\]

By setting \( z = 1 \), we obtain:

\[
q_0 + \pi_0 = \frac{1 - \lambda \overline{Y}}{1 - \lambda \overline{Y} + \lambda \overline{V}} \tag{14}
\]

Then \( \Pi(z) \) and \( Q(z) \) become:

\[
\Pi(z) = \frac{1 - \lambda \overline{Y}}{1 - \lambda \overline{Y} + \lambda \overline{V}} \frac{Y^*(\lambda - \lambda z)(1 - V^*(\lambda - \lambda z))}{Y^*(\lambda - \lambda z) - z} \tag{15}
\]

\[
Q(z) = \frac{1 - \lambda \overline{Y}}{1 - \lambda \overline{Y} + \lambda \overline{V}} V^*(\lambda - \lambda z)
\]

The PGF for the number of packets in the queue immediately after packet departure is

\[
\Pi_d(z) = \frac{\Pi(z) - \pi_0 + Q(z) - q_0}{(1 - \pi_0 - q_0)z} \alpha_2(z)\alpha_3(z)
\]

\[
= \frac{(1 - \lambda \overline{Y})}{\overline{V}} \frac{(1 - V^*(\lambda - \lambda z))}{Y^*(\lambda - \lambda z) - z} \alpha_2(z)\alpha_3(z) \tag{16}
\]

and the mean number of packets left is \( \overline{L} = \Pi_d(1) = \overline{c_2} + \overline{c_3} - \frac{1}{2} + \overline{a_1^{(2)}} + \frac{A^{(2)}}{2(1-\rho)} - \frac{\rho}{2(1-\rho)} \), where \( \overline{a_1^{(2)}} \) denotes the second moment of the number of packet arrivals during vacation time and \( A^{(2)} \) denotes second moment of the number of packet arrivals during packet service cycle.

Probability distribution of the waiting time in the node buffer can be found by using the observation that, under the FIFO serving discipline, the number of packets left in the queue after a packet departure is equal to the number of packets which have arrived to the queue while the target packet was in the system. Therefore,

\[
\Pi_d(z) = T_d(\lambda - \lambda z) = W^*(\lambda - \lambda z)Y^*(\lambda - \lambda z) \tag{17}
\]

By using the substitution \( s = \lambda - \lambda z \), we obtain the LST of the packet waiting time as

\[
W^*(s) = \Pi_d \left( 1 - \frac{s}{\lambda} \right) \frac{1}{Y^*(s)} \frac{1}{1 - V^*(s)}
\]

\[
= \frac{(1 - \lambda \overline{Y})}{\overline{V}} \frac{C^*(s)S^*(s)}{Y^*(s)} \frac{(1 - V^*(s))}{[\lambda Y^*(s) + s - \lambda]}
\]

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The averaged packet waiting time is
\[
W = -\frac{dW^*}{ds}\bigg|_{s=0} = \frac{V^{(2)}}{2V} + \frac{\lambda Y^{(2)}}{2(1 - \rho)} + \frac{1 - \rho}{V}(\overline{C} - \overline{S} - \overline{Y})
\]
where \(Y^{(2)} = \frac{d^2Y^*(s)}{ds^2}\bigg|_{s=0}\) denotes the second moment of packet service cycle time, while \(V^{(2)} = \frac{d^2V^*(s)}{ds^2}\bigg|_{s=0}\) denotes the second moment of vacation time.

**V. PERFORMANCE EVALUATION**

In order to evaluate the performance of the proposed scheme we have conducted two experiments. First, we consider a piconet with \(M = 18\) nodes. We have set the time unit to a single sensing slot, packet duration time to \(k_d = 10\) time units, acknowledgment duration to one basic slot, the superframe duration to \(s_f = 100\) time units, and superframe part dedicated to the reporting of sensing results and bandwidth reservation to \(\Delta = 20\) time units. Packet arrival rate per node was varied between \(\lambda = 0.0005\) and \(0.003\) packets per slot; the penalty coefficient was \(k_p = 0.2 \ldots 1.2\). We have assumed that destinations for packet transmissions are uniformly distributed over the piconet nodes. Using these numerical values, we have solved the system of equations (4) to (10) using all members of the series for \(P_0\). Numerical calculations were performed using Maple 11 by Maplesoft, Inc. [8].

Fig. 3 shows the performance parameters obtained in this experiment. The diagrams in the upper row show the offered load and the probability that transmission and reception will occur in the same superframe. We have deliberately chosen the area of the graph where \(\rho\) is close to 1 in order to show the limits of the stable network operation. We notice that under high load the areas for \(\rho > 0.75\) and \(P_{\text{theta}} < 0.75\) coincide.

The diagrams in the bottom row show the average packet service cycle, average piconet cycle, and average packet waiting time. We note that area where \(P_{\text{theta}} < 0.99\) in Fig. 3(a) corresponds to the area where \(\overline{C} < s_f < \Delta\). However, parameter \(P_{\text{theta}}\) does not need to be close to 1 for the stable operation. As Figs. 3(a) and 3(e) show, stability is affected for \(P_{\text{theta}} < 0.8\). This is also confirmed by the diagram in Fig. 3(c) where packet service cycle exceeds two superframes. We also notice a sharp increase of packet waiting delay when the offered load approaches the stability limit of 1.

In the second experiment, we have varied the piconet size \(M\) in the range 5...20 and kept the transmission penalty coefficient constant at \(k_p = 1\). Fig. 4 shows the various performance parameters for this case. The diagrams confirm our findings from the previous experiment, and suggest that the values parameters \(\lambda\), \(M\) and \(k_p\) should be chosen in order to ensure acceptable packet delay and sensing time.

**VI. CONCLUSION**

In this paper we have investigated one possible scheme of interaction between transmission and sensing in cognitive personal area networks. The scheme conforms to the 1-limited round robin service policy, where nodes can transmit only single packet they’ve had at the moment of applying for the bandwidth using the first-come, first-served policy. In addition, nodes need to perform sensing duty after each transmitted...
packet. We have modeled the effect of packet reception of the node which might preempt, but not reduce sensing activity. In this manner, total sensing time is not affected; instead, any reception actually contributes to the packet delay. The 1-limited policy is simple to implement and fair to all nodes. However, it suffers from the overhead associated to each transmitted packet which decreases the stable operation region. The impact of this decrease on the delay performance of the network has been evaluated.

REFERENCES


