On the Feasibility of Using WiFi White Spaces for Opportunistic M2M Communications

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***Abstract*—Machine to machine (M2M) communications enable autonomous communication between devices and are an integral part of the Internet of Things (IoT). This paper evaluates the feasibility of opportunistic M2M communication in the unlicensed industrial, scientific and medical (ISM) band and its coexistence with existing WiFi networks. Using a $BMAP/G/1/K$ queuing model, we evaluate the duration and frequency of idle periods or "white spaces" in WiFi networks, that may be opportunistically used for M2M communication. Our results show that white spaces occur frequently and are sufficiently long to facilitate opportunistic M2M communications.**

***Index Terms*—WiFi, white spaces, M2M communications.**

I. Introduction

The IoT is expected to fuel a large scale increase in the number of devices in the Internet [1], and these devices will primarily use M2M communications for information exchange. While M2M communications may use both licensed and unlicensed bands, this paper focuses on unlicensed spectrum due to the cost of licensed bands. However, unlicensed bands such as the ISM band are crowded with many existing networks such as WiFi, Zigbee and Bluetooth. The objective of this paper is to explore the possibility of using unlicensed bands for opportunistic M2M communications. In particular, we focus on the ISM band and its most popular user: WiFi.

It is well known that many networks, including WiFi, are underutilized, with frequent periods of inactivity [2]. We refer to the periods when a WiFi network is idle as the "white spaces". If these white spaces are long enough and occur frequently, they may be opportunistically exploited for M2M communications and we consider this as the communication paradigm in this paper. The M2M communication is assumed to be opportunistic, and thus should not interfere with the primary users in the WiFi network. Such scenarios may occur in homes or offices where M2M devices such as sensors transfer information during white spaces in the WiFi network where humans are the primary users. To evaluate the feasibility of the opportunistic M2M communication paradigm described above, we develop a model for the distribution of the lengths of white spaces, and the frequency of their appearance. The design of a protocol that exploits WiFi white spaces for opportunistic M2M communication is left for future work.

In related literature, a trace driven study of white spaces in lightly loaded WiFi networks, for exploitation by ZigBee applications is presented in [3]. This model is empirical, whose parameters have to be calculated from actual traces of network traffic. A model for white spaces is developed in [4], assuming that the traffic arrival process is a Markov Modulated Poisson Process (MMPP). In contrast, this paper considers a more general arrival process. Also, closed form expressions for the expected length of a busy period, and the fraction of time the channel is idle are presented. Opportunistic M2M communication has also been considered for TV white spaces [5], [6]. However, the activity of primary users of TV spectrum are quite distinct from users of WiFi networks.

To characterize the white spaces, this paper models a WiFi network as a $BMAP/G/1/K$ queue. The periods where the queue is empty correspond to the periods where the nodes in the network do not transmit packets and thus model the white spaces. We model the packet arrivals in the WiFi network as a batch Markovian arrival process (BMAP). The service time of the queue corresponds to time taken to transmit a packet in the WiFi network, including the time for channel access. The model provides a characterization of the probability distribution of the length of white spaces, the number of white spaces per unit time, as well as the expected time between two successive white spaces. Our results show that WiFi white spaces provide ample opportunities for opportunistic M2M transmissions under a wide range of operating conditions.

The rest of the paper is organized as follows. Section II presents the based model for characterizing white spaces in WiFi networks. Section III presents simulation results to verify the proposed model. Finally, Section IV concludes the paper.

II. An Analytic Model for WiFi White Spaces

We consider a WiFi network with n nodes and one access point (AP). Given that the major fraction of traffic in most networks is in the downlink (AP to nodes), we consider the situation where the traffic flow at each node consists of streams of packets from the Internet that are forwarded to them by the AP. While the presence of uplink traffic affects the idle times, the relatively low volume of uplink traffic makes their impact quite small and is thus neglected. For each node, the packet arrival process at the AP is modeled as a BMAP. BMAPs are chosen as the arrival process because of their versatility and ability to accurately model a wide range of processes including voice, video and long range dependent traffic [7].

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White spaces correspond to times when the WiFi network is idle. Idle times may occur due to two factors: when nodes do not have any packets to send, or protocol related silent periods such as backoffs, short interframe spaces (SIFS) and distributed coordination function interframe spaces (DIFS). Protocol related silent periods are of the order of tens of micro-seconds and thus not long enough for opportunistic M2M communications. Thus our model for white spaces only considers the scenarios where the MAC layer queues are empty. We characterize the network activity by modeling the AP's operation as a $BMAP/G/1/K$ queue. The white spaces in the WiFi network then correspond to the times when the queue is empty. The model uses BMAP arrivals and a general service time distribution $h(t)$ (corresponding to the behavior of the IEEE 802.11 MAC protocol) with mean Θ. K is the buffer size at the AP and the model has a single server since only one node may successfully transmit at any time.

A. Arrival Model

A BMAP is a continuous-time Markov chain whose underlying Markov process is irreducible and its infinitesimal generator is a $m \times m$ matrix D [8]. The sojourn time in each state is exponentially distributed with parameter λ_i, $\lambda_i \geq -D_{ii}$. At the end of each sojourn time, a transition occurs from current state i to state j and that transition may or may not correspond to an arrival epoch. With probability $p_i(0,j), 1 \leq j \leq m, j \neq i$, the transition to state j occurs without an arrival. With probability $p_i(k,j), k \geq 1, 1 \leq j \leq m$, there is a transition to state j with a batch arrival of size k. We have,

$$\sum_{\substack{j=1\\ j\neq i}}^{m} p_i(0,j) + \sum_{k=1}^{\infty}\sum_{j=1}^{m} p_i(k,j) = 1. \tag{1}$$

This system can be represented by a sequence of matrices $D_k, k \geq 0$, which are defined as

$$\begin{aligned}
(D_0)_{ii} &= -\lambda_i, 1 \leq i \leq m,\\
(D_0)_{ij} &= \lambda_i p_i(0,j), 1 \leq i,j \leq m, j \neq i,\\
(D_k)_{ij} &= \lambda_i p_i(k,j), k \geq 1, 1 \leq i,j \leq m,
\end{aligned}$$

with $\sum_{k=0}^{\infty} D_k = D$. The stationary distribution of this Markov process is denoted by π and is given by

$$\pi D = 0, \qquad \pi e = 1,$$

where e is an unit column vector of dimension m. The average arrival rate λ for this process is given by,

$$\lambda = \pi \sum_{k=1}^{\infty} k D_k e. \tag{2}$$

The matrix generating function of the BMAP arrival process is given by

$$D(z) = \sum_{k=0}^{\infty} D_k z^k, for |z| \leq 1. \tag{3}$$

The arrival process for each node is modeled as an independent BMAP with generator matrix $D^{(i)}$, $1 \leq i \leq n$. The aggregate arrival process at the AP is then the superposition of the n BMAPs, which in turn is a BMAP. The generator matrices for the resultant process are given by

$$D_k = D_k^{(1)} \oplus D_k^{(2)} \oplus \cdots \oplus D_k^{(n)}, \qquad \forall k = 0,1,2,\cdots \tag{4}$$

where $\oplus$ denotes the Kronecker-sum defined as

$$A \oplus B = (A \otimes I_B) + (I_A \otimes B),$$

and $\otimes$ represents the Kronecker-product defined as

$$A \otimes B = \begin{bmatrix} a_{11}B & a_{12}B & \cdots & a_{1m}B \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}B & a_{n2}B & \cdots & a_{nm}B \end{bmatrix}.$$

B. Service Time Distribution

To derive the service time distribution, consider a new packet arrival at the AP destined for an arbitrary node i, $1 \leq i \leq n$. At the instant of the packet's arrival, the queue may be either empty or non-empty, and we denote these as *state 0* and *state 1*, respectively. The service times for these two cases are as follows.

State 0: When packets arrive at an empty queue, they move to the head-of-the-line (HoL) immediately and the AP begins the medium access procedure. After listening to the channel for T_{DIFS} corresponding to a DIFS, the AP transmits a request-to-send (RTS) frame of duration T_{RTS}. In response to the RTS frame, the destination waits for a SIFS period, T_{SIFS}, and sends a clear-to-send (CTS) frame, of duration T_{CTS}. Once the CTS frame is received by the AP, it waits for T_{SIFS} and then transmits the data. The data rate used depends on the estimated channel conditions. If the receiver decodes the packet correctly, it sends an acknowledgment (ACK), of duration T_{ACK}, after time T_{SIFS}. Since there are no collisions in our scenario, the service time in *state 0* consists of constant terms except for the data transmission time, T_D, which depends on the packet size (with distribution $f(x)$) and the data rate R. The Laplace-Stieltjes Transform (LST) of the service time is then given by

$$\begin{aligned}
H_0(s) &= LST[T_{DIFS} + T_{CA} + T_D + T_{SIFS} + T_{ACK}]\\
&= LST[T_C + T_D] \; = \; \mathrm{e}^{-sT_C} + LST\left[\frac{f(x)}{R}\right]
\end{aligned} \tag{5}$$

where $T_{CA} = T_{RTS} + T_{CTS} + 2T_{SIFS}$ is the time taken by the RTS-CTS exchange and $T_C = T_{CA} + T_{DIFS} + T_{SIFS} + T_{ACK}$ denotes the total constant time in each transmission.

State 1: When a packet arrives at a non-empty queue, it first has to wait for the packets already in the queue to be transmitted, and its service time starts only when it moves to the HoL. The service starts with a DIFS period and the AP then has to undergo a random back-off (to prevent channel hogging). The back-off timer is chosen as a uniformly distributed integer between 0 and minimum contention window CW, denoted by $U[0, CW]$. The backoff time is then given by $U[0, CW]T_{slot}$ where T_{slot} is the length of a backoff slot. Once the backoff counter decrements to 0, the transmission process follows as in *state 0*. The LST of the service time in *state 1* is then

$$\begin{aligned}
H_1(s) &= LST[U[0-CW]T_{slot} + T_C + T_D]\\
&= T_{slot}\frac{1-\mathrm{e}^{-sCW}}{sCW} + \mathrm{e}^{-T_C s} + LST\left[\frac{f(x)}{R}\right].
\end{aligned} \tag{6}$$

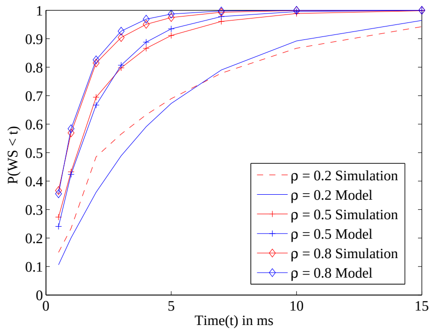

Fig. 1. The distribution of duration of white spaces (WS) for different traffic intensities.

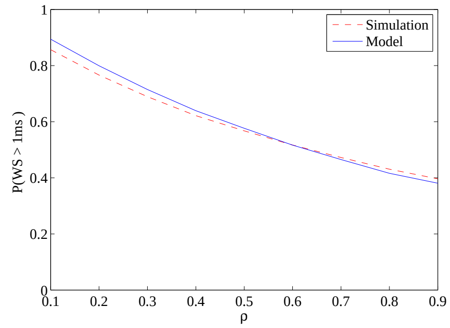

Fig. 2. $P(WS \geq 1ms)$ for different values of ρ.

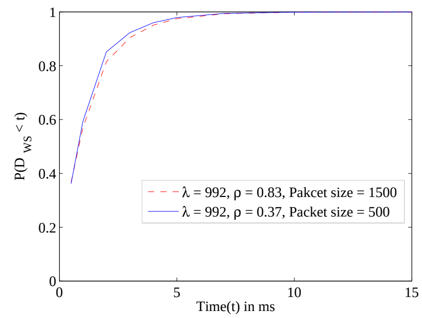

Fig. 3. Distribution of duration of white spaces for different packet sizes with same arrival rates.

Overall service time H(s): Let p_0 denote the steady state probability that the queue is empty. The LST of the overall service time is then given by

$$H(s) = p_0 H_0(s) + (1-p_0)H_1(s)$$
$$= (1-p_0)\left[T_{slot}\frac{1-\mathrm{e}^{-sCW}}{sCW}\right] + \left[\mathrm{e}^{-sT_C} + LST\left[\frac{f(x)}{R}\right]\right]. \quad (7)$$

The expected duration of the service time, Θ, is given by

$$\Theta = -\frac{d}{ds}\, H(s)\big|_{s=0}. \quad (8)$$

C. Duration of White Spaces

The cumulative distribution function (CDF) of the duration of white spaces is denoted by $F_{WS}(t) = P(WS \leq t)$, $t \geq 0$. To obtain this CDF, we define $u^*(t, j|i)$ as the probability that the queue's idle period is less than t and the arrival process's phase at the start of the subsequent busy period is j, given that the phase at the end of the preceding busy period was i:

$$u^*(t, j|i) = P(WS < t, j|i) \qquad \forall\, i, j \in 1, 2, \cdots, m. \quad (9)$$

Let $U^*(t)$ denote a $m\times m$ matrix with elements $u^*(t, j|i)$, $1 \leq i, j \leq m$. The transform of $U^*(t)$ is given by [9]:

$$\mathrm{U}^*(s) = [sI - D(0)]^{-1}(D(1) - D(0)) \quad (10)$$

where I is a $m\times m$ identity matrix. From (3), we have, $D(0) = D_0$ and $D(1) - D(0) = D_1 + D_2 + D_3 + \cdots$. The transform in (10) can be numerically inverted (e.g. following the procedure in [10]) to obtain the conditional probabilities $u^*(t, j|i)$. The CDF of the duration of white spaces is then

$$P(WS < t) = U^*(t)e\pi \quad (11)$$

where e is an unit column vector. (11) shows that the duration of white spaces does not depend on the service time distribution, or in turn, on packet lengths or the transmission rate.

D. Expected Duration of White Spaces

From (10), the expected duration of white spaces is given by

$$E[U^*(t)] = (-1)\left.\frac{d(U^*(s))}{ds}\right|_{s=0} = ((-D_0)^{-1})^2(D(1) - D_0). \quad (12)$$

$E[U^*(t)]$ represents a matrix of conditional expectations. Unconditioning, we have

$$D_{WS} = E[U^*(t)]e\pi = ((-D_0)^{-1})^2(D(1) - D_0)e\pi. \quad (13)$$

In any time interval, the expected fraction of time that the queue is idle is p_0. Then, dividing p_0 by $E[WS]$ gives the average number of white spaces in unit time, N_{WS}. Thus

$$N_{WS} = \frac{p_0}{((-D_0)^{-1})^2(D(1) - D_0)e\pi}. \quad (14)$$

E. Expected Length of Busy Periods

Another quantity of interest is the expected length of busy periods which indicates the time between successive opportunities for possible M2M communications. Since busy and idle periods alternate, in any given interval of time, on an average, the number of busy periods (N_{BP}) is equal to number of idle periods, i.e.,

$$N_{BP} = N_{WS} \quad (15)$$

The fraction of time the queue is busy in unit time is $\rho = 1 - p_0$. Also, in an unit of time, there are N_{BP} busy periods. Thus the average duration of a busy period, D_{BP}, is given by

$$D_{BP} = \frac{1-p_0}{N_{WS}} = \left(\frac{1}{p_0} - 1\right)((-D_0)^{-1})^2(D(1) - D_0)e\pi. \quad (16)$$

F. Solving the BMAP/G/1/K Queue

One of the quantities required to determine the idle and busy periods as described in the previous subsections is p_0. To obtain p_0 for a $BMAP/G/1/K$ queue, we use the following procedure. For a given arrival process D, we first calculate its stationary distribution π, and the overall arrival rate λ. Using (8), the average service time is given by

$$\Theta = -\frac{d}{ds}H_S(s)\Big|_{s=0} = (1-p_0)T_{slot}\frac{CW}{2} + T_c + E\left[\frac{f(x)}{R}\right]. \quad (17)$$

Let $T_{data} = E[f(x)/R]$. Using $\rho = \lambda\Theta$, we also have

$$p_0 = 1 - \lambda\Theta = 1 - \lambda((1-p_0)T_{slot}\frac{CW}{2} + T_c + T_{data}). \quad (18)$$

Solving the equation above for p_0, we have

$$p_0 = \frac{\lambda(T_{slot}CW + 2(T_c + T_{data})) - 2}{\lambda T_{slot}CW - 2}. \quad (19)$$

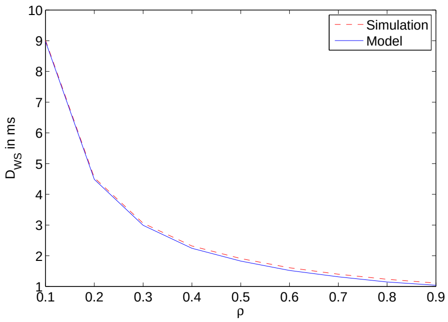

Fig. 4. Average duration of white spaces for different values of ρ.

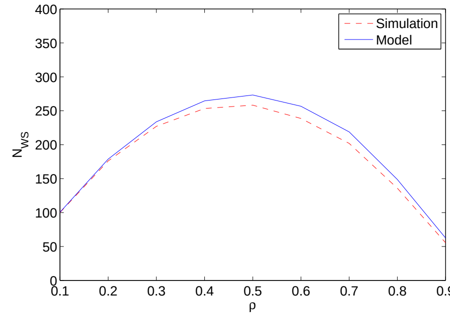

Fig. 5. Average number of white spaces per unit time for different values of ρ.

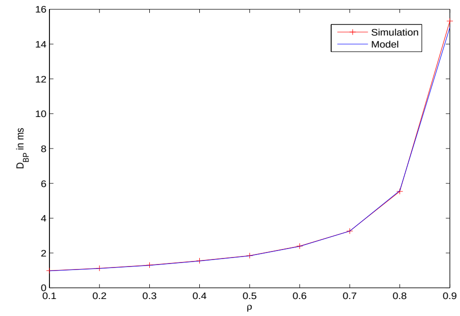

Fig. 6. Average duration of busy periods for different values of ρ.

III. Simulation Results

This section presents simulation results, using the NS3 simulator, to verify the accuracy of the proposed model. We consider a IEEE 802.11g network with one AP and four nodes, reflecting typical home scenarios. The traffic destined for each node is generated according to an independent, 2-state ($m = 2$) BMAP whose parameters D_k, $k = 0, 1, 2$ are varied to obtain different traffic intensities, ρ. Each simulation was run for 3600 seconds, and each result is averaged over 5 runs. The size of each packet was 1400 bytes, and the other parameters are $R = 18$ Mbps, $T_C = 94$ μs, $T_{slot} = 9$ μs and $K = 100$.

The CDF of the duration of white spaces, for various values of ρ, is shown in Fig. 1. As expected, white spaces of longer duration occur more frequently when the network utilization (or packet arrival rate) is lower. To evaluate the feasibility of opportunistic M2M communications in these scenarios, we consider the likelihood of white spaces greater than 1 ms (e.g., it takes 0.78 ms to transmit a 50 byte packet at 512 Kbps). Figure 2 shows $P(WS > 1$ ms$)$ as a function of ρ. It can be seen that even at high loads of $\rho = 0.9$, 40% of the white spaces are longer 1 ms.

The CDF of the duration of white spaces (given in (11)) is independent of the service time. This is shown in Fig. 3 which plots the CDF of the length of white spaces for two different packet sizes. While changing the packet size changes the service time and ρ, the distribution of white spaces does not change. Figure 4 shows the average duration of white space (D_{WS}) for different traffic intensities. We note that D_{WS} decreases quickly with increasing traffic. Changing the packet size does not change the average duration of white space because the distribution itself remains unchanged.

Finally, in order for opportunistic M2M communications to be feasible, there should be sufficient opportunities for them to transmit. Figure 5 shows the average number of white spaces per second as function of ρ. The number of idle periods per unit time first increases as the network utilization increases, before decreasing again. This is because when the load is low, we have longer idle periods but the number of idle periods is small. As the traffic load increases, the idle periods are interrupted by frequent transmissions of data packets which decreases the average duration of idle period, but the number of idle periods increases. However, beyond a certain point, an increase in the load results is long busy periods thereby decreasing both the average duration and number of idle periods. However, white spaces of sufficiently long duration occur frequently enough to allow meaningful communications, even at high loads. For example, when $\rho = 0.9$, the average duration of a white space is $1.11ms$ and the average number of white spaces per second is 60.

IV. Conclusion

This paper evaluates and demonstrates the feasibility of opportunistic M2M communications in the ISM band, in the presence of significant WiFi traffic. The WiFi network activity is modeled as a BMAP/G/1/K queue and expressions for the distribution of white spaces, average duration of white spaces and average number of white spaces per second are evaluated.

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