On Exploiting White Spaces in WiFi Networks for Opportunistic M2M Communications

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***Abstract*—Machine to machine (M2M) communications are expected to form one of the fundamental building blocks of the future Internet of Things (IoT). In view of the scarcity of spectrum and the service requirements of traditional users, providing network access to the extremely large number of devices in IoT and M2M scenarios is one of the fundamental problems for network designers and operators. As a possible solution to this issue, this paper explores the possibility of using the unlicensed industrial, scientific and medical (ISM) band for supporting M2M communications while co-existing with traditional users of this band. Since IEEE 802.11 or WiFi based networks are the most common networking technology in the ISM band, this paper presents an evaluation of "white spaces" in WiFi networks (i.e. periods where the WiFi network is not using the channel) that may be used opportunistically for M2M communications. Using a MMPP/G/1/K queue to model the operation of a WiFi access point, we characterize the WiFi white spaces in terms of their frequency, duration, and their probability distribution. Our results show that WiFi white spaces provide considerable transmission opportunities that may be exploited for M2M communications.**

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

I. Introduction

The Internet of Things will comprise of a large number of embedded devices that permeate our living and working environments in order to provide automation, and facilitate various services that enhance our quality of life [1]. A significant fraction of the data generated and exchanged in the IoT will be between machines. Some studies estimate that by 2020 there will be around 50 billion devices connected to internet with large portion of them being M2M communication based devices [2]. While M2M communication is becoming a market-driving force for many intelligent real-time applications, facilitating large scale M2M is filled with many challenges. Of these, one of the most critical challenges is to provide efficient channel access to the large number of devices [3].

The problem of providing channel access for M2M communications has received significant attention in industry and academia. Many standardization bodies have tried to address this problem by implementing various degrees of support for M2M communication and resolving the channel access bottleneck in cellular systems like Long Term Evolution (LTE), 3rd Generation Partnership Project (3GPP) and WiMax [4], [5]. While such solutions require licensed bands that are expensive, a viable alternative for wireless M2M communication is to use the unlicensed ISM band. Currently, the ISM band is used by many local area networking protocols such as IEEE 802.11 and Bluetooth. Thus access mechanisms for M2M communications that opportunistically use the ISM band would be of great interest. For M2M devices to coexist with existing services in the ISM band, it is important to first ascertain whether there are enough available channel resources for M2M communications while satisfying the requirements of existing networks. Since WiFi networks are ubiquitous and the most popular users of the ISM band, this paper focuses on evaluating the "white spaces" or idle periods in a WiFi network. Such a characterization will allow network designers to ascertain the extent to which WiFi white spaces can be used for opportunistic M2M communication. While it has been noted that many WiFi networks are largely underutilized [6], an exact characterization and evaluation of the idle periods is necessary to ensure that M2M communications can co-exist with WiFi networks. To address the problem for characterizing and evaluating the suitability of WiFi white spaces for opportunistic M2M communications, this paper presents an analytic model to characterize the white spaces in a WiFi network. The paper considers a WiFi network with a single access point and an arbitrary number of users. The activity on the network is then modeled using a MMPP/G/1/K queuing model. The proposed model characterizes the white spaces in the WiFi network by evaluating the idle periods of the queue. The model provides a number of metrics to understand the characteristics of WiFi white spaces including the fraction of time the channel is idle, the probability distribution of the length of an idle period, average duration of idle period, and how frequently the channel becomes idle. Our results show that WiFi white spaces provide adequate opportunities for M2M transmissions under a large range of operating conditions. The proposed model has been verified using simulations conducted in the NS3 simulation tool.

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The rest of the paper is organized as follows. Section II presents a survey the related literature. Section III presents the MMPP/G/1/K queue based model for characterizing the distribution and average duration of white spaces in WiFi networks. Section IV presents the simulation results to verify the proposed model. Finally, Section V concludes the paper.

II. Literature Survey

The development of medium access control protocols and channel access techniques for M2M communications has received considerable attention in the recent past. While many of the proposed protocols present enhancements to existing technologies such as cellular networks to support M2M communications [7], [8], or require a dedicated channel [9], [10], cognitive protocols that exploit unused spectrum for M2M communications have also been proposed [11], [12]. However, existing cognitive radio protocols for M2M communications are based on exploiting TV white spaces or in networks with centralized controllers that can inform users about unused resources.

Our focus in this paper is on modeling white spaces in WiFi networks with multiple users. In [13] the authors have tried to model WiFi white spaces in physical layer for exploitation by ZigBee applications. The proposed models are based on analyzing real traffic traces collected under lightly loaded network conditions. However, increasingly a major source of network traffic is multimedia streaming applications that offer considerable load on WiFi access points. Also, the Pareto distribution used in [13] to model the idle period can only account for white spaces greater than 1 ms. Another disadvantage of that model is that it is an empirical model whose parameters have to be calculated from actual traces of network traffic. In this paper we present an analytic model to obtain the distribution of white-spaces in WiFi networks under realistic traffic conditions. We also consider heavily loaded network scenarios where the network traffic is based on multiple video streams that are streamed by the users of the WiFi network.

We also note that the unlicensed ISM band is available to all kinds of heterogeneous devices and their coexistence has been widely studied in existing literature. In [13] the authors propose a MAC protocol which detects and uses the idle time slices in WiFi transmission. In [14] the authors suggest a mechanism by which the WiFi devices can be muted periodically by a fake-PHY preamble header broadcast from the ZigBee devices. However, these studies do not present a thorough study or characterization of the white spaces in a WiFi network. Our paper addresses this open problem and provides a framework and insights to facilitate more efficient use of WiFi white spaces.

III. An Analytic Model for WiFi White Spaces

In this section we present an analytic model to characterize the white spaces in a WiFi network. The proposed approach is based on using a queueing model to characterize the activity of the nodes in the network.

We consider a WiFi network with one access point (AP) and n leaf nodes or devices. This paper focuses on WiFi networks in home and similar scenarios where the major traffic is in the downlink direction, i.e., from the AP to the nodes. Thus we assume that the AP is receiving packets from the Internet and transmitting them to the n leaf nodes. The packet arrival process at the AP intended for each node is modeled as a Markov Modulated Poisson Process (MMPP) with an arbitrary number of states r. We use a MMPP based arrival model because they are quite suitable for a large variety of traffic types such as voice, video as well as long range dependent traffic [15], [16]. We model the MAC layer queue at the AP by a MMPP/G/1/K model with MMPP arrivals and a general service time distribution $h(t)$ with mean Θ. The service time distribution $h(t)$ is derived subsequently in this section.

A. Arrival Model

The traffic arrival process at the AP for each node is modeled as a MMPP. In a MMPP the arrivals take place according to a Poisson process and the rate of arrival λ depends on the phase of underlying Markov chain Q. Thus an MMPP can be described by its arrival rate matrix Λ and transition rate matrix Q. For the traffic corresponding to node i , $1 \leq i \leq n$, the matrices Q_i and Λ_i are given by

$$Q_i = \begin{bmatrix} -\sigma_1 & \sigma_{12} & \cdots & \sigma_{1r} \\ \sigma_{21} & -\sigma_2 & \cdots & \sigma_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{r1} & \sigma_{r2} & \cdots & -\sigma_r \end{bmatrix} \tag{1}$$

$$\Lambda_i = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_r \end{bmatrix}. \tag{2}$$

Let q be the steady state probability vector of the Markov chain. Then q satisfies the equations $qQ_i = 0$ and $qe = 1$ where e is a unit vector. The overall arrival rate λ_{Total} is given by $(\Lambda_i q)e$. The aggregate arrival process at the AP is superposition of n MMPPs corresponding to the arrivals for each of the n nodes. It is well known that superposition of many MMPPs is also an MMPP [17]. The generator matrix Q and the arrival matrix Λ for composite MMPP can be obtained from the individual generator Q_i and Λ_i as

$$Q = Q_1 \oplus Q_2 \oplus \cdots \oplus Q_n$$
$$\Lambda = \Lambda_1 \oplus \Lambda_2 \oplus \cdots \oplus \Lambda_n$$

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

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

B. Service Time Distribution

To evaluate the MMPP/G/1/K queue to model the MAC layer behavior of the AP, we need the appropriate service time distribution $h(t)$. To characterize this service time distribution, we consider the operation of the AP when a new packet arrives for an arbitrary node i, $1 \leq i \leq n$. When a packet arrives at the AP for node i, the queue at the AP may be in one of the following two states: *a*) **State S0:** the queue is empty; and *b*) **State S1:** the queue is non-empty. Next we consider the service time for the two cases separately.

1) **State S0:** If the packet arrives at the AP when its queue is empty, it joins the head-of-the-line (HoL) and is immediately considered for transmission. The AP listens to the channel for a time T_{DIFS} corresponding to the distributed interframe space (DIFS). If the channel is found to be idle, the AP transmits a request-to-send (RTS) frame of duration T_{RTS}. After receiving the RTS frame, the destination node responds with a clear-to-send (CTS) frame after waiting for time T_{SIFS} (corresponding to a short interframe space (SIFS)). After receiving the CTS frame, the AP waits for time T_{SIFS} and then transmits the data with a data rate based on the channel conditions. Finally, the receiver node sends an acknowledgment (ACK) after time T_{SIFS} if it receives the data successfully. If there is no collision (as will be the case in a network with only downlink traffic from the AP), the only random variable here is the data transmission time, T_D, which is dependent on the size of the packet and the data rate selected by the AP and the leaf node. Let p_0 denote the probability that the queue is empty at an arbitrary instant. Then the Laplace-Stieltjes Transform (LST) of the service time in case S0 is given by

$$\begin{aligned} H_{S0}(s) &= LST[T_{DIFS} + T_{CA} + T_D + T_{SIFS} + T_{ACK}] \\ &= LST[T_C + T_D] \\ &= \mathrm{e}^{-sT_C} + LST\left[\frac{f(x)}{R}\right] \end{aligned} \tag{3}$$

where T_{CA} is the total time taken for the RTS-CTS exchange which is equal to $T_{RTS}+T_{CTS}+2\times T_{SIFS}$ and T_C is the total constant time in every transmission in case S0, which is equal to $T_{CA} + T_{DIFS} + T_{SIFS} + T_{ACK}$. The variable T_D can be chosen to have an arbitrary distribution depending on packet size distribution $f(x)$ and chosen data rate R. It is reasonable to assume that within a busy period of the queue at the MAC layer of the AP, the data rate does not change abruptly.

2) **State S1:** Next we consider the case where the queue is non-empty when a packet arrives (we call this the "tagged" packet). For such a packet, the service time starts only when the last of the enqueued packets leaves the queue. Once the tagged packet comes to the head of the queue, it first has to wait for a DIFS period and a random back-off chosen from time $U[0, CW]T_{slot}$ where $U[a, b]$ denotes a discrete, uniformly distributed random variable between a and b, CW is the minimum contention window size and T_{slot} is the length of a backoff slot. The backoff counter is decreased by one for every idle slot and the AP transmits the packet when the counter decrements to zero. Recall that this paper only considers downlink traffic from the AP to the nodes. Thus there are no other transmissions that can interrupt the backoff counter at the AP. The time taken by the AP to transmit the packet is the same as in Eqn. (3). Including the time spent in backoff, the LST of the service time for case S1 becomes

$$\begin{aligned} H_{S1}(s) &= LST[U[0-CW]T_{slot} + T_C + T_D] \\ &= T_{slot}\frac{1-\mathrm{e}^{-sCW}}{sCW} + \mathrm{e}^{-T_C s} + LST\left[\frac{f(x)}{R}\right] \end{aligned} \tag{4}$$

3) **Total service time H(s):** To obtain the total service time we combine the service times for the cases S0 and S1, weighted by their respective probabilities p_0 and $1-p_0$, respectively. Thus the LST of the total service time is given by

$$\begin{aligned} H_S(s) &= p_0 H_{S0}(s) + (1-p_0) H_{S1}(s) \\ &= (1-p_0)\left[T_{slot}\frac{1-\mathrm{e}^{-sCW}}{sCW}\right] + \\ &\quad \left[\mathrm{e}^{-sT_C} + LST\left[\frac{f(x)}{R}\right]\right] \end{aligned} \tag{5}$$

The average service time, Θ, is given by

$$\Theta = -\frac{d}{ds}\, H_S(s)|_{s=0} \tag{6}$$

C. Distribution of Duration of White Spaces

White spaces in a WiFi network correspond to the time when the network is idle, i.e., there are no packets to be transmitted in any of the nodes. Note that the times when a node is in backoff is not counted as a white space or idle period since a packet is in "service". Also, the periods corresponding to backoffs of the WiFi nodes (of the order of tens of microseconds) is too small for use by M2M nodes. Thus characterizing the distribution of white spaces is equivalent to modeling the distribution of the idle periods of the system where the queues at the nodes are empty.

The cumulative distribution function, D_{WS}, of the duration of white spaces is defined as the probability of the event $P(WS \le t)$ for all times $t \ge 0$. To obtain this distribution, we define $u^*(t, j|i)$ as probability that the idle period of the MMPP/G/1/K queue is less than t and the phase of arrival process at the start of subsequent busy period is j, given that arrival phase at the end of preceding busy period was i:

$$u^*(t, j|i) = P(WS < t, j|i) \qquad \forall\ i, j \in 1, 2, \cdots, r. \tag{7}$$

Thus $u^*(t, j|i)$ can be expressed in a $r \times r$ matrix $U^*(t)$. The transform of this matrix distribution $U^*(t)$ is given by [18]

$$\mathrm{U}^*(s) = [sI + \Lambda - Q]^{-1}\Lambda \tag{8}$$

where I is an $r \times r$ identity matrix.

To obtain the distribution of the white spaces, the parameters of the arrival process, Q and Λ, are first used in Equation (8) to obtain a transform of the probability matrix $U^*(t)$. This transform is then numerically inverted (e.g. following the inversion procedure from [19]) to obtain a matrix with the conditional probabilities $u^*(t, j|i)$. The CDF of the duration of white spaces is then given by

$$P(WS < t) = U^*(t)eq \tag{9}$$

where e is an unit column vector and q is the steady state probability vector of the Markov chain Q satisfying $qQ = 0$

and $qe = 1$. It is interesting to note that the distribution of the durations of the white spaces does not depend on the service time distribution (which in turn depends on the packet lengths).

D. Expected Duration of White Spaces

In this section we derive an expression for the expected duration of the white spaces, based on the distribution obtained in the previous section. The transform of the CDF of the duration of white spaces, $U^*(s)$, is given by Eqn. (8). The expected value of $U^*(t)$ is then given by

$$\begin{aligned} E[U^*(t)] &= (-1)\ \frac{d(U^*(s))}{ds}\bigg|_{s=0} \\ &= (-1)\ \frac{d(sI+\Lambda-Q)^{-1}\Lambda}{ds}\bigg|_{s=0}. \end{aligned}$$

Let $Y = sI + \Lambda - Q$. Then we have,

$$\begin{aligned} E[U^*(t)] &= (-1)(-1)\ (Y)^{-1}\frac{d(sI+\Lambda-Q)}{ds}(Y)^{-1}\Lambda\bigg|_{s=0} \\ &= (sI+\Lambda-Q)^{-1}I(sI+\Lambda-Q)^{-1}\Lambda\big|_{s=0} \\ &= ((\Lambda-Q)^{-1})^2\Lambda. \end{aligned}$$

$E[U^*(t)]$ is a matrix of conditional expectations. The unconditional expectation is then given by

$$\begin{aligned} E[WS] &= E[U^*(t)]eq \\ &= ((\Lambda-Q)^{-1})^2\Lambda eq. \end{aligned} \tag{10}$$

It is straightforward to note that the average number of white spaces (N_{WS}) in unit time is given by

$$\begin{aligned} N_{WS} &= \frac{\text{Fraction of time queue is idle}}{\text{Average duration of a white space}} \\ &= \frac{p_0}{((\Lambda-Q)^{-1})^2\Lambda eq} \end{aligned} \tag{11}$$

E. Solving the MMPP/G/1/K Queue

Our model for the distribution of the white spaces is based on modeling the WiFi network as a MMPP/G/1/K queue whose service time distribution is given by Eqn. (5). For completeness, this section provides an overview of the procedure for calculating the steady state probabilities of the queue length and in particular p_0, the probability that the queue is empty (used in the calculation of the frequency of white spaces). The mean service time Θ is given by Eqn. (6) and is a function of p_0. To obtain p_0 for a MMPP/G/1/K queue, we use the analysis from [20] and list the equations below for completeness. Consider the embedded Markov chain consisting of the service completion instants at the queue. Let $\pi(k)$ (respectively, $p(k)$) be the r-dimensional vector whose j^{th} element is the limiting probability at the imbedded epochs (respectively, at an arbitrary time instant) of having k packets in the queue, $k = 0, 1, \cdots, K-1$ (respectively, $k = 0, 1, \cdots, K$), and the MMPP being in phase j. Define the matrix sequence $\{\mathrm{C}_k\}$ as

$$\mathrm{C}_{K+1} = \left[\mathrm{C}_k - \mathrm{UA}_k - \sum_{v=1}^{k}\mathrm{C}_v\mathrm{A}_{k-v+1}\right]\mathrm{A}_0{}^{-1} \tag{12}$$

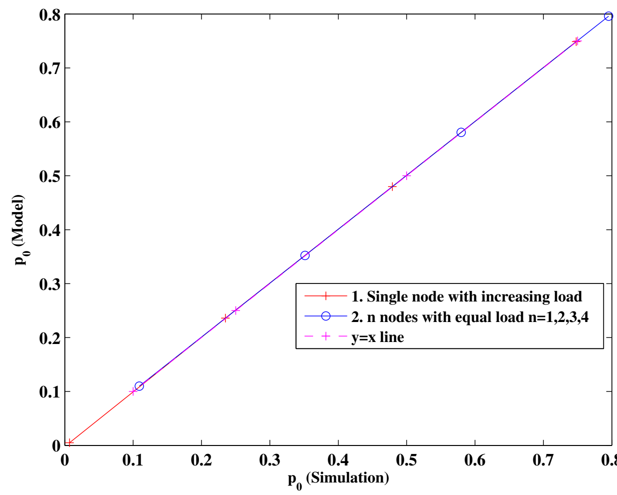

Fig. 1. Comparison of values of p_0 obtained the simulations and the proposed model.

for $k = 1, 2, \cdots, K-2$, with $\mathrm{C}_0 = \mathrm{I}, \mathrm{C}_1 = (\mathrm{I}-\mathrm{UA}_0)A_0{}^{-1}$ and I is a $r \times r$ identity matrix. The (k, l)-th element of the matrix A_v denotes the conditional probability of reaching phase l and having v arrivals at the end of service time, starting from phase k. The matrices A_v can easily calculated using an iterative procedure [17]. The probability vectors $\pi(k)$ is then given by

$$\pi(0)\left[\sum_{v=0}^{K-1}\mathrm{C}_v + (\mathrm{I}-\mathrm{U})\mathrm{A}(\mathrm{I}-\mathrm{A}+eq)^{-1}\right] = q, \tag{13}$$

and $\pi(k) = \pi(0)\mathrm{C}_k, k = 1, 2, \cdots, K-1$. The vector $p(0)$ can then be calculated as

$$p(0) = \xi\pi(0)(\Lambda-\mathrm{Q})^{-1}\Theta^{-1} \tag{14}$$

where $\xi = [1 + \pi(0)(\Lambda-\mathrm{Q})^{-1}\Theta^{-1}e]^{-1}$. To complete the analysis, we note that the probability that the queue is empty, p_0, is given by $p(0)e$. However, p_0 is used in the expression for the service time, which in turn is used to evaluate $p(0)$. To obtain p_0, we use an iterative technique: we start with an arbitrary value of p_0 in $(0, 1)$ and use it to compute the service time and $p(0)$. The new value of p_0 given by $p(0)e$ is then used to recalculate the service time and $p(0)$. This process continues till the values of p_0 and $p(0)e$ converge.

IV. Simulation Results

This section presents simulation results to verify the proposed model. The simulations were carried out using the NS3 simulation software. The simulated network topology reflects a home or office scenario where a single IEEE 802.11 access point serves as the network gateway for a number of devices. Our study focuses on heavy traffic scenarios since they are more likely to cause fewer and smaller white spaces. Consequently, we assume that each of the users in the network is downloading a video from the Internet (via the access point). The video traffic for each node is generated according to an independent, 2-state ($r = 2$) MMPP with parameters $\sigma_1 = 8$,

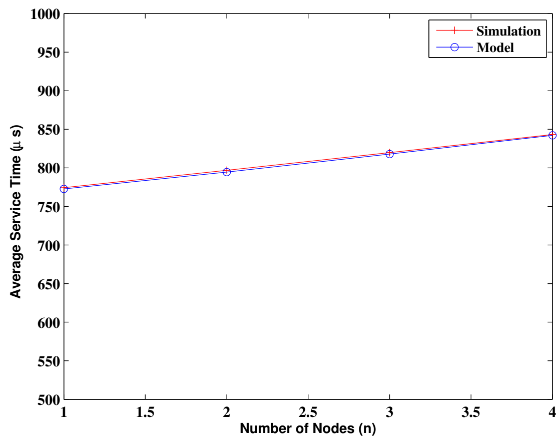

Fig. 2. Comparison of average service time for different values of n obtained from the simulations and the proposed model.

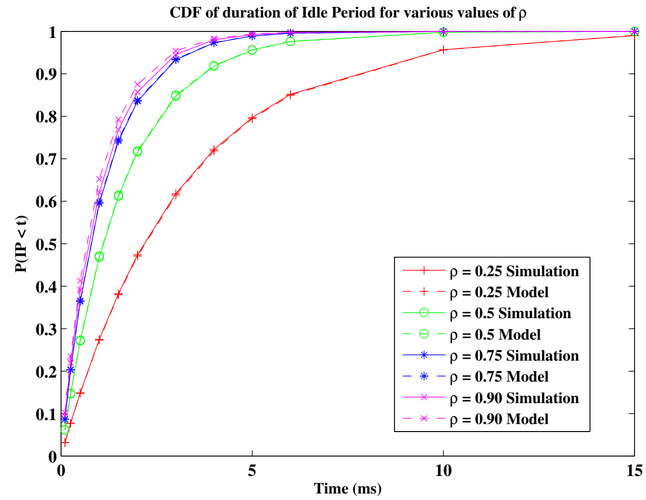

Fig. 3. The distribution of duration of white spaces (WS) for different traffic intensities.

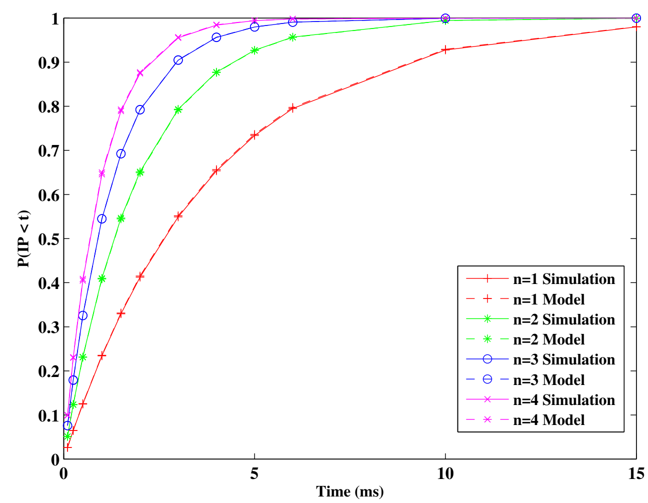

Fig. 4. The distribution of duration of white spaces (WS) for different numbers of devices and traffic intensities.

$\sigma_2 = 2$ and λ_1, λ_2 are varied to get different values of traffic intensity ρ. Note that MMPPs have been shown to accurately characterize video traces in existing literature [15], [16]. The length of each simulation was 3600 seconds, and each result is averaged over 5 runs. The channel data rate was fixed at $R = 18$ Mbps, $T_C = 94\mu s$, $T_{slot} = 9\mu s$ and the size of each packet was 1500 bytes. A buffer size of $K = 100$ was used.

To evaluate the accuracy of the MMPP/G/1/K queueing model for the wireless network, we first compare the simulation results for the fraction of time the channel is idle with that from the analysis (given by p_0). Figure 1 compares the p_0 values obtained from the model and simulations. The accuracy of the results are reflected by how close the results are to the $x = y$ line. In the first case, we consider a network with a single device where the traffic arrival rate is varied to simulate scenarios with different levels of utilization (0.25, 0.50, 0.75 and 0.90). The increasing values of p_0 indicate decreasing arrival traffic and we note the closeness of the simulation and analytic results. In the second case we consider the scenario where the number of devices, n, is varied from 1 to 4 in order to increase the level of network utilization. Again, we note the close match between the analytic and simulation results. We also note that the value of p_0 does not decrease linearly with the increase in number of nodes. This can be explained by Figure 2 which shows the increase in the average service time as n is increased, as obtained from Equation (6) and compares it with the values obtained from simulations. As the arrival traffic increases, the service time also increases because a larger fraction of the packets now have to go through a random back-off before being transmitted.

Next, we consider the accuracy of the proposed model for the distribution of the duration of white spaces. Figure 3 shows the distribution $P(WS \leq t)$ for a single node with increasing traffic arrival rates. The corresponding results for different numbers of nodes are shown in Figure 4. In all cases, the likelihood of experiencing longer idle periods (i.e. white spaces) decreases as the traffic intensity increases. Also, we note the close match between the simulation and analytic results.

The average duration of white spaces as given by the analytic and simulation results is compared in Figure 5. As expected, as the number of devices n increases, the average duration of the white spaces decreases. It is interesting to note that for the scenarios considered in our simulations, the average duration of white spaces is in range of $1-3$ ms. Even at high load conditions when $n = 4$ the average length of white spaces of 0.982 ms. Such idle periods are long enough to send M2M packets under general conditions.

Finally, in order for M2M communications to successfully communicate using white spaces, there should be sufficient opportunities for them to transmit. Figure 6 shows the average number of white spaces per second, as obtained from the simulations and our model, for different values of n. We note that the number of idle periods per unit time first increases

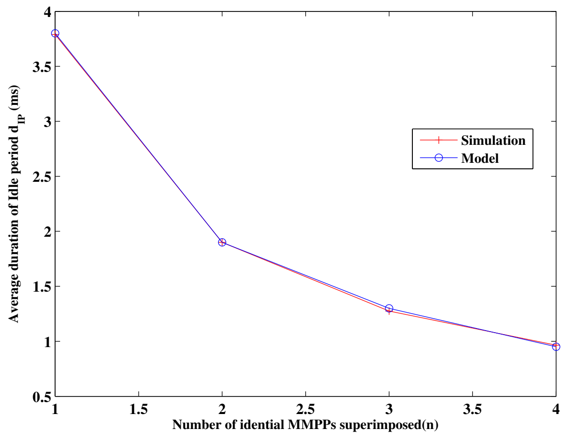

Fig. 5. Average duration of white spaces for different values of n.

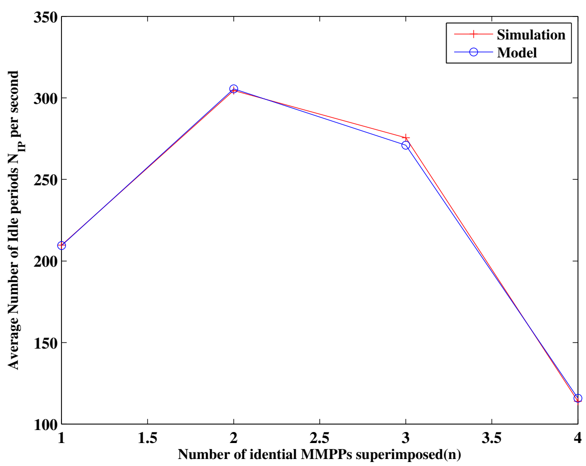

Fig. 6. Average number of white spaces per unit time for different values of n.

as the network utilization increases (roughly utilization levels of 0.5), before decreasing again. This can be explained as follows: when the traffic load is low, we have longer idle periods but the number of idle periods is small. As the traffic load increases, the average duration of an idle period decreases but number of idle periods increases. However, as the traffic load increases beyond a certain point, both the average duration and number of idle periods start decreasing. From the perspective of M2M communications, we note that even at high loads, white spaces occur frequently enough to allow meaningful communications. For example, at high loads when $n = 4$, the average duration of a white space is 0.98 ms and the average number of white spaces per second is 94 (i.e. on average, there are 94 idle periods each with average duration of 0.98 ms in a time interval of 1 second).

V. Conclusion

This paper addressed the problem of characterizing the white spaces or idle periods in a WiFi network and evaluated their suitability for enabling opportunistic M2M communications. To characterize the distribution of white spaces, we model the underlying WiFi network as a MMPP/G/1/K queue and use it to obtain the average duration as well as the frequency of occurrence of the white spaces. Our results show that WiFi networks have adequate white spaces to allow opportunistic M2M communications. The accuracy of the proposed model has been verified through extensive simulations.

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