Characterization of White Spaces in Wi-Fi Networks for Opportunistic M2M Communications

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***Abstract*—With the expected explosion in the number of devices in the Internet-of-Things (IoT), the availability of spectrum for these devices to connect to the network is a challenging problem. A possible solution to this problem is the use of opportunistic machine-to-machine (M2M) communications where IoT devices exploit idle periods of primary users (i.e. users with higher priority on spectrum usage) to transmit their data. The feasibility of such opportunistic M2M communication depends on the temporal characteristics of the availability of unused spectrum. Considering the unlicensed bands where Wi-Fi devices are the primary users, we present a $BMAP/G/1/nK$ queue based model to characterize the duration and frequency of the periods available for opportunistic M2M communications. Our results show that M2M devices may co-exist with W-Fi networks, and even in Wi-Fi networks with high loads, there are adequately long and frequent idle periods that can be used to support opportunistic M2M communications.**

***Index Terms*—Wi-Fi, white spaces, M2M communications, IoT.**

I. Introduction

Spectrum is a scarce and expensive resource in wireless communication. Current efforts aimed at developing access technologies for M2M communications consider the use of both licensed and unlicensed spectrum. Solutions being proposed and implemented in the licensed spectrum for M2M devices include efforts such as those by 3GPP (3rd Generation Partnership Project) for LTE (Long Term Evolution) to allow large scale M2M communication [1]. However, licensed spectrum based access technologies may not be cost-effective for many scenarios and thus they have not achieved widespread acceptance by the industry as well as the research community. On the other hand, unlicensed spectrum such as the ISM (industrial, scientific and medical) bands are free of licensing costs. However, there is a proliferation of devices and technologies such as Wi-Fi, ZigBee and Bluetooth in these bands and thus it is expected that the implementation of M2M communication technologies in these bands will face challenges related to interference, spectrum management, and co-existence. However, even though existing unlicensed ISM bands in most places are usually already occupied by devices (e.g. Wi-Fi), these devices may not be active at all times and such bands are occasionally heavily underutilized, even in urban areas [2]. In this paper we study the possibility of using unlicensed ISM bands for opportunistic M2M communication in presence of other technologies, with specific focus on Wi-Fi. The objective of this paper is to develop an analytic model to characterize the duration and frequency of appearance of silent periods in Wi-Fi networks that may be used for opportunistic M2M communications. The model and its results are expected to serve as validation of the feasibility of opportunistic M2M communication and facilitating the development of practical, opportunistic MAC protocols for M2M devices.

In the notion of opportunistic communication considered in this paper, users are classified in two groups: primary and secondary. Primary (Wi-Fi) users are given first priority for using the spectrum and when the primary users are idle, i.e., when the spectrum is unused, secondary (M2M) users may use the spectrum for opportunistic communication. Thus the performance of primary users is not affected and the overall network utilization is increased. We call the periods when the spectrum is unused as the "white spaces". Whether these white spaces are useful for opportunistic communication or not depends on their statistical characteristics, such as their frequency of occurrence, the duration of white spaces, and the time between two successive occurrences of white spaces. For opportunistic M2M communication to be feasible, there should be white spaces that are adequately long and such white spaces should occur sufficiently frequently. To evaluate the feasibility of opportunistic M2M communication, this paper develops an analytic model for statistically characterizing the white spaces when the primary users are Wi-Fi devices.

While various technologies such as Bluetooth, ZigBee and Wi-Fi are the common occupants of the ISM bands, Wi-Fi is the most prevalent. Not only is its coverage range larger that the others, it also offers higher data rates and Wi-Fi is often the preferred means of network access in homes and offices. Consequently, this paper assumes that the primary users of the ISM band use Wi-Fi for their channel access. With Wi-Fi devices as the primary users, the *white spaces are the times when none of the Wi-Fi nodes in the network have any data to transmit.* If Wi-Fi devices have packets to transmit in their medium access control (MAC) layer queues and are thus engaged in their channel access mechanism, the M2M nodes refrain from transmissions as they may interfere with the backoff or transmissions of Wi-Fi nodes.

To evaluate the feasibility of opportunistic M2M communication in the presence of Wi-Fi traffic, this paper develops an analytic model to characterize the statistical properties of the white spaces. The model is based on characterizing the activity of the Wi-Fi network using a queueing model and modeling the white spaces as the periods when the queue is empty. Using the

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versatile batch Markovian arrival process (BMAP) to model the arrivals at the Wi-Fi nodes, we use a $BMAP/G/1/nK$ queue to model the behavior of the aggregate network. The model presents closed form expressions for the length of white spaces, number of white spaces per unit time, the fraction of time the channel is idle, and the expected length of busy periods for a Wi-Fi network with both downlink and uplink traffic. The accuracy of the proposed model has been verified using extensive simulations. Our results show that even at high loads (e.g. network load of 0.9) white spaces occur frequently (more than 100 per second) and are sufficiently long (longer than 1 ms) to accommodate opportunistic M2M communications.

The rest of the paper is organized as follows. Section II presents the related work and Section III presents the model for characterizing white spaces in Wi-Fi networks. Section IV presents simulation results to verify the proposed model and discusses the application of our model for developing opportunistic protocols for M2M communication. Finally, Section V concludes the paper.

II. Related Work

Channel access mechanisms for M2M communication introduce a number of challenges including those of scalability, spectrum usage and co-existence, and quality of service issues [3]. A majority of the existing work is focused on the use of dedicated spectrum for M2M communications, including both licensed and unlicensed bands [4], [5], [6], [7]. M2M communications based on exploiting unused spectrum and the use of cognitive protocols have been proposed in [8], [9]. Unlike this paper's focus on the ISM bands and Wi-Fi networks, the cognitive protocols in [8], [9] are based on exploiting TV white spaces. These protocols require advanced antenna system for their operation and users are informed about unused resources by centralized controllers.

Along the lines of this paper where the objective is to model the white spaces in Wi-Fi network for opportunistic M2M communications, a model for Wi-Fi white spaces is presented in [10] for exploitation by ZigBee applications. The model presented in [10] is empirical and obtained by analyzing traffic traces collected under lightly loaded network conditions. This model may not be valid in scenarios such as offices, or homes with streaming multimedia traffic where Wi-Fi access points are considerably loaded. Additionally, the white spaces are modeled as a Pareto distribution in [10], and can only consider white spaces longer than 1 ms. In contrast, this paper considers more realistic network scenarios and can accommodate heavily loaded networks. In [11] and [12], a simplistic model for Wi-Fi white spaces is developed that only considers the downlink traffic from the access point (AP) to the nodes. In this model, there are no collisions in the Wi-Fi network and the AP can transmit without any competition for channel resources since the Wi-Fi devices do not send any packets. In contrast, this paper considers both uplink and downlink traffic in the Wi-Fi network. The presence of uplink traffic changes and complicates the model since we now have collisions and the resulting backoffs in the network, and the characteristics of the white spaces change significantly.

Finally, we note that unlicensed ISM bands may be used by heterogeneous devices and access technologies, and existing literature has investigated their coexistence under various scenarios. A MAC protocol that detects idle times in Wi-Fi transmissions and uses them for ZigBee transmissions is proposed in [10]. In [13] a mechanism for ZigBee transmissions is proposed where ZigBee devices periodically mute Wi-Fi devices by broadcasting fake-PHY preamble headers. In [14] the authors propose a method for sending clear-to-send (CTS) messages from an access point to block Wi-Fi transmission so that ZigBee devices can complete their communication cycles. These protocols do not utilize existing Wi-Fi white spaces; rather, they block the Wi-Fi traffic to facilitate M2M communication. Also, these protocols do not provide any characterization or insights into the duration and frequency of the white spaces. The objective of this paper is to address the problem of characterizing the white spaces in a Wi-Fi network, evaluate their feasibility for opportunistic M2M communications, and provide insights that can facilitate more efficient use of Wi-Fi white spaces.

III. Model for Wi-Fi White Spaces

The white spaces in a Wi-Fi network correspond to the times when there are no transmissions in the network. The medium in a Wi-Fi network is idle when none of the nodes in the network have any packets to transmit, or when the transmissions are stifled due to the IEEE 802.11 protocol (e.g. when nodes are in backoff, short interframe spaces (SIFS) and distributed coordination function interframe spaces (DIFS) periods). The IEEE 802.11 protocol induced periods of silence are fairly short (of the order of few tens of micro-seconds) and not long enough to be utilized for opportunistic M2M communications. Consequently, our model only considers the idle times that occur when the MAC layers queues at all the devices (i.e. nodes and AP) in the network are empty.

To evaluate the distribution of the white spaces, this section presents a model that characterizes the states of the MAC layer queues of the devices in the Wi-Fi network. We consider a Wi-Fi network with n nodes: one AP and $n-1$ users. The (uplink) traffic generated at each node as well as the (downlink) traffic at the AP are modeled as batch Markovian arrival processes. Unlike simple arrival processes such Poisson processes, BMAPs can effectively account for batch arrivals. In addition, BMAPs can model dependent inter-arrival times, non-exponential inter-arrival times, and correlations in the batch sizes. BMAPs have also been shown to accurately model a wide range of traffic including voice, video and long range dependent traffic [15]. Note that arrival processes such as phase type processes, Markov modulated Poisson processes (MMPPs), and interrupted Poisson processes are special cases of BMAPs.

While the traffic arrivals at the devices are independent, their service process (i.e. the transmissions) are correlated because they share the medium as per the rules of the IEEE 802.11 MAC protocol. Since a white space corresponds to the time when the queues at *all* the devices are empty, we model the activity of the entire network using a single, finite buffer queue. The model uses BMAPs to account for the arrivals at all the devices, and a general service time distribution $h(t)$ (based on the behavior of the IEEE 802.11 MAC protocol) with mean $\frac{1}{\mu}$. The buffer size at each of the nodes and the AP is assumed to be K packets. The model has a single server since in a shared medium controlled using the IEEE 802.11 MAC protocol, only one node may successfully transmit at any time. Thus, we model the overall system using a $BMAP/G/1/nK$ queue and this section obtains the distributions necessary to obtain the steady-state distribution of the queue length, and uses it to characterize the white spaces. Also, in this paper we assume that all packet losses are caused by collisions and there are no channel errors. This is to keep the analysis tractable and focus our attention on the MAC layer behavior.

A. Arrival Model

This paper uses BMAPs to model the traffic arrival process at each device in the network due to their versatility. A BMAP is a continuous-time Markov chain with an arbitrary number of states, m, and an irreducible underlying Markov process, and we denote its infinitesimal generator, D, using a $m \times m$ matrix [16]. In each state, the sojourn time is exponentially distributed with parameter λ_i, with $\lambda_i \geq -D_{ii}$. At the end of a sojourn time, the process transitions from the current state i to state j and that transition may or may not correspond to an arrival epoch. The transition to state j occurs without an arrival with probability $p_i(0,j), 1 \leq j \leq m, j \neq i$ and with probability $p_i(k,j), k \geq 1, 1 \leq j \leq m$, the transition to state j comes with a batch arrival of size k. We have,

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

A BMAP can then be represented using a set 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 $\sum_{k=0}^{\infty} D_k = D$. We denote the stationary distribution of this Markov process by π and it 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 the BMAP is then 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 at each node and the AP is modeled as an independent BMAP with generator matrix $D^{(l)}$, $1 \leq l \leq n$, with $D^{(n)}$ representing the arrival at the AP and $D^{(l)}$, $1 \leq l \leq n-1$, representing the arrivals at the nodes. The aggregate arrival process in the network is the superposition of the n BMAPs and this aggregate process is also a BMAP. The generator matrices for the aggregate 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

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

The interested reader is directed to pages 2-4 of [16] for an excellent tutorial on BMAPs.

B. Service Time Distribution

In this section we obtain the service time distribution of packets in the Wi-Fi network. Since we are modeling the entire network as a single queue, the service time is defined as the time required by the network to transmit a packet, irrespective of the device which transmits the packet. In this queueing model for the network, the service time starts as soon as a packet is transmitted (assuming at least one of the devices in the network has packets to send) and ends when a packet is successfully transmitted in the network. The service time of a packet thus comprises of protocol related times such as DIFS, SIFS and back-off intervals, time spent in collisions, as well as the time taken to transmit the data and acknowledgment (ACK) packets in the channel. We next present a detailed derivation of the service time in the Wi-Fi network. The analysis proceeds in two steps. First we consider the individual queue at each device in the network. Next we use parameters from the individual queues to develop a model that considers the entire network as a single queue and thereby calculate the distribution of the white spaces.

In the Wi-Fi network, when a node generates an uplink packet to be sent or the AP receives a downlink packet to be forwarded to the nodes, the packet enters the MAC layer queue at the respective device. The devices then contend for the channel using IEEE 802.11's CSMA/CA protocol [17]. As per this protocol, a node first senses the channel before transmitting. If the channel is sensed idle for the duration of a DIFS period, the node can immediately transmit the data (or RTS) packet. However, if the channel is observed to be busy, the device goes into backoff. The discrete-time, exponential backoff mechanism in Wi-Fi works as follows: If the channel is sensed to be busy, it initializes a backoff counter, BC, with a random integer value uniformly distributed between 0 and $CW_{min} - 1$ (called the contention window). This value of the backoff counter is denoted by

$$BC = U[0, CW_{min} - 1] \tag{5}$$

where $U[a,b]$ denotes a discrete uniform random variable between a and b. The backoff counter is in units of back-off slots and is decremented whenever the channel is observed to be idle, and frozen when the channel becomes busy. A node may proceed with a transmission when the backoff counter reaches 0. In case the transmitted packet experiences a collision, the contention window is doubled to $[0, 2CW_{min} - 1]$ and BC is re-initialized with a random value within this window. In case of successive collisions, the contention window keeps doubling till it reaches an upper limit denoted by CW_{max}. Thus, the upper limit on the contention window after γ unsuccessful transmission attempts is given by: $\min\{CW_{max} - 1, 2^{\gamma}CW_{min} - 1\}$. Once a packet is successfully transmitted, the contention window is reset to $[0, CW_{min} - 1]$.

Let the probability that a transmission attempt by node u is unsuccessful, i.e., the probability of a collision be denoted by p_u for $1 \leq u \leq n$. p_u is a conditional probability and represents the probability of collision of a packet that is being transmitted. As in existing literature, we assume that the collision probability is independent of the node's backoff stage [18], [19]. Consider an arbitrary packet at node u that is contending for transmission. Then, the probability mass function (pmf) of the upper limit on the contention window, CW is given by

$$P\left(CW = W\right) = \begin{cases} p_u^{\gamma-1}(1-p_u), & \text{for } W = 2^{\gamma-1}CW_{min} - 1 \\ p_u^r, & \text{for } W = CW_{max} - 1 \end{cases} \tag{6}$$

where $r = log_2(CW_{max}/CW_{min})$ and $1 \leq \gamma \leq r$ [19]. The probability that the back-off counter for the packet takes on a value x, $BC = x, 1 \leq x \leq CW_{max}$, is then given by [19]:

$$P\left(BC = x\right) = \begin{cases} \left[\sum_{\gamma=0}^{r-1} \frac{p_u^{\gamma}(1-p_u)}{2^{\gamma}CW_{min}} + \frac{p_u^r}{CW_{max}}\right] & 1 \leq x \leq CW_{min} \\ \left[\sum_{\gamma=y}^{r-1} \frac{p_u^{\gamma}(1-p_u)}{2^{\gamma}CW_{min}} + \frac{p_u^r}{CW_{max}}\right] & 2^{y-1}CW_{min} + 1 \leq x \leq 2^{y}CW_{min} \\ \frac{p_u^r}{CW_{max}} & 2^{r-1}CW_{min} + 1 \leq x \leq CW_{max} \end{cases} \tag{7}$$

where $1 \leq y < r$. The collision probability at any node u can be expressed in terms of the average backoff window. In the saturated traffic case where each packet is backlogged immediately, each packet starts out with a contention window of $[0, CW_{min} - 1]$. The transmission is successful with probability $1 - p_u$ and the average number of backoff slots experienced such a packet is $(CW_{min} - 1)/2$. With probability $p_u(1 - p_u)$ the first transmission fails and the packet is successfully transmitted in second attempt (using a contention window of $[0, 2CW_{min} - 1]$) and the average number of backoff slots in the second attempt is $(2CW_{min} - 1)/2$. Proceeding along these lines for packets that need further attempts before they are successfully transmitted, the average number of backoff slots experienced by packets at node u is given by [19]:

$$\begin{aligned} \overline{W}_u &= (1-p_u)\frac{CW_{min}-1}{2} \\ &\quad + p_u(1-p_u)\frac{2(CW_{min}-1)}{2} + \cdots \\ &\quad + p_u^r(1-p_u)\frac{2^r(CW_{min}-1)}{2} \\ &\quad + p_u^{r+1}\frac{2^r(CW_{min}-1)}{2} \\ &= \frac{1-p_u-p_u(2p_u)^r}{1-2p_u}\frac{CW_{min}-1}{2}. \end{aligned} \tag{8}$$

While the equation above assumes saturated traffic conditions at each node, it may also be used for relating the collision probability to the average window size for non-saturated cases with a slight modification. When the devices in the network have non-saturated traffic conditions, arrivals at a node with an empty queue may be transmitted immediately if the channel is idle, and thus it is not necessary that all packets experience backoff at least once. Let ρ_u, $1 \leq u \leq n$, denote the utilization of the queue at node u. Then the average number of backoff slots experienced by an unsaturated node is approximated as $\rho_u \overline{W}_u$ to compensate for the times when the packets do not experience any back-off.

The arrival process at each node is a BMAP and we denote the average packet arrival rate at node u by λ_u, as given by (2). Also, we denote the the packet service rate of node u by μ_u packets per unit time and the queue utilization at a node is then given by $\rho_u = \lambda_u/\mu_u$. To evaluate the collision probability experienced by the packets at a node, we consider a tagged node that transmits in a given slot. This transmission from the tagged node experiences a collision if one or more of the remaining $n-1$ nodes also transmit in this slot. Let $P(SE)_j$ denote the probability that node v does not transmit in an arbitrary slot. Then the probability that the transmission from the tagged node (say node u) experiences a collision is given by

$$p_u = 1 - \prod_{\substack{v=1 \\ v \neq u}}^{n} P(SE)_v. \tag{9}$$

Note that the expression above uses the commonly used decoupling approximation which assumes that the decision to transmit or not in a slot by a node is independent of similar decisions by other nodes [18], [19]. We use the notation QE to denote "queue empty" and QNE to denote "queue not empty". $P(SE)_u$ is then given by

$$\begin{aligned} P(SE)_u &= P(SE|QE)_u P(QE)_u + P(SE|QNE)_u P(QNE)_u \\ &= 1 \cdot (1-\rho_u) + \rho_u P(SE|QNE)_u. \end{aligned}$$

In the expression above, $P(SE|QE)_u = 1$ since if a queue is empty, it does not transmit. Also, the probability that the queue at node u is empty is given by $P(QE)_u = 1 - \rho_u$. Now, a queue may be non-empty in a slot due to two reasons: it is backlogged with packets or if the queue started off as empty but a packet arrived during the slot. Of these, the probability of the second case is quite small since we are only interested in stable queues (i.e. with bounded arrival rates) and the duration of a backoff slot is orders of magnitude smaller than packet transmission times. Since the probability that backlogged node u transmits in an arbitrary slot is $\frac{1}{\overline{W}_u}$, the probability that it does not transmit in a slot is $\frac{\overline{W}_u-1}{\overline{W}_u}$. Then, $P(SE|QNE)_u$ can be approximated by $\frac{\overline{W}_u-1}{\overline{W}_u}$. We then have,

$$\begin{aligned} P[SE]_u &= 1-\rho_u+\rho_u\frac{\overline{W}_u-1}{\overline{W}_u} \\ &= 1-\frac{\rho_u}{\overline{W}_u}. \end{aligned} \tag{10}$$

Combining (8),(9) and (10), the conditional collision probability at node u is given by

$$p_u = 1-\prod_{\substack{v=1\\v\neq u}}^{n}\left(1-\rho_v\left(\frac{1-2p_v}{1-p_v-p_v(2p_v)^r}\frac{2}{CW_{min}-1}\right)\right). \tag{11}$$

To evaluate the p_u's using the expression above, we need to obtain the utilization at each node, which in turn depends on the average service time at each node. To evaluate the average service time at node u, we first note that each packet at the node, on average, spends $\rho_u\overline{W}_u$ slots in backoff. Also, due to the long term fairness of the exponential backoff mechanism, on an average $\sum_{v=1,v\neq u}^{n}\rho_v$ transmissions from other nodes occur between two transmissions from tagged node u. These transmissions add $\sum_{v=1,v\neq u}^{n}\rho_v T_{s,v}$ seconds to the service time at node u, where $T_{s,v}$ is the average transmission time of a packet at node v. Also, each packet transmission attempt by node u results in a collisions with probability p_u. Then, before a packet is successfully transmitted, on an average it experiences $p_u/(1-p_u)$ collisions. Similarly, the average number of collisions experienced by the transmissions from other nodes is $\sum_{\substack{v=1\\v\neq u}}^{n}\rho_v p_v/(1-p_v)$, and these add $\sum_{\substack{v=1\\v\neq u}}^{n}\rho_v T_{c,v}p_v/(2(1-p_v))$ seconds to the service time of the tagged packet at node u. Here, $T_{c,v}$ denotes the expected duration of a collision at node v and the factor of 2 in the denominator reflects the first degree approximation that each collisions involves only two nodes. Adding all the contributing components, the expected service time at node u is given by

$$\begin{aligned} \frac{1}{\mu_u} = &\sum_{\substack{v=1\\v\neq u}}^{n}\rho_v T_{s,v}+\sum_{\substack{v=1\\v\neq u}}^{n}\rho_v T_{c,v}\frac{p_v}{2(1-p_v)}+\rho_u\overline{W}_u\delta \\ &+T_{s,u}+T_{c,u}\frac{p_u}{2(1-p_u)} \end{aligned} \tag{12}$$

where $\overline{W}_u$ is given by (8) and δ is the duration of a backoff slot. Using $\rho_u=\lambda_u/\mu_u$ in the expression above and rearranging the terms, we get,

$$\rho_u = \frac{\sum_{\substack{v=1\\v\neq u}}^{n}\rho_v\left(T_{s,v}+T_{c,v}\frac{p_v}{2(1-p_v)}\right)+T_{s,u}+T_{c,u}\frac{p_u}{2(1-p_u)}}{\left(\frac{1}{\lambda_u}-\overline{W}_u\delta\right)}. \tag{13}$$

The values of ρ_u and p_u, $1\leq u\leq n$, can then be obtained by solving (11) and (13) simultaneously.

C. Network Model: Aggregate Queue

The white spaces in a Wi-Fi network are defined as instances when the Wi-Fi network is idle and in our model, these correspond to the instances when the MAC layer queues of all nodes in the network are empty. Since each node in the network has BMAP arrivals and a finite buffer space of K, they may be modeled as a $BMAP/G/1/K$ queue. Let p_{0u} denote the probability that the queue at node u is empty at an arbitrary instant with

$$p_{0u} = 1-\rho_u. \tag{14}$$

Then an approximation of the probability that the system is idle, p_0, is given by

$$p_0 = \prod_{u=1}^{n} p_{0u}. \tag{15}$$

This approximation may be inaccurate in many scenarios since the operation of the queues at the nodes is not independent. The nodes share a common medium and the transmissions from one node affect the service times, and thus the queue length distributions of other nodes. To develop a more accurate characterization of the probability that the system is idle and use it to develop a model for the white spaces, we now present a model that looks at the combined behavior of all nodes in the network.

To model the combined behavior of all the nodes, the operation of the network is modeled using a single queue. The arrivals at this queue correspond to the aggregate of the arrivals at all nodes. As discussed in Section III-A, the arrival process at each node is modeled as an independent BMAP and the aggregate arrival process considering the arrivals at all nodes is given by the superposition of n BMAPs, which in turn is also a BMAP as given by (4). The service time of the aggregate queue corresponds to the time between two consecutive successful transmissions in the network (irrespective of the nodes that transmit the packets) for cases when a successful transmission leaves behind a non-empty system. For example, if node u completes a successful transmission at time t_1 and the next successful transmission in the network is completed by node v at time t_2, the service time for the packet in the aggregate queue is considered as t_2-t_1. In case a transmission leaves behind an empty system, the service time is the duration from the next arrival to the system and the first subsequent successful transmission. Since each node in the network is assumed to have a buffer of size K, the buffer space of the aggregate queue is taken to be nK. This approximation does does not affect the accuracy of the model for the white spaces since white space calculations are largely unaffected by packet loss rates. Finally, since only one packet may be successfully transmitted in the network at any time, the aggregate model for the network models the system using a $BMAP/G/1/nK$ queue.

To model the service time distribution of the aggregate queue, we consider the possible events between two successful transmissions. After a successful transmission in the network, there are two possibilities: either the aggregate queue becomes empty (AQE) (i.e. none of the nodes in the network has any packet to send) or it is not empty (AQNE) (i.e. at least one node has a packet to send). If the aggregate queue is empty, this marks the beginning of a white space. The white space ends with the arrival of the first packet in the network (irrespective of the node) and this packet is transmitted immediately since the channel is idle. This packet does not experience a collision because the probability of arrival events at two or more nodes at the same instant is zero. On the other hand if the aggregate queue is not empty, one or more nodes in the network have packets to send and these nodes resume their backoff process. A transmission attempt is made in the network after one (or more, in case of identical backoff counters) of the nodes decrements its backoff counter to zero. Since nodes unfreeze their backoff counters and resume their backoff, we call the number of backoff slots till the first node decrements its counter to zero as the *residual backoff*. Also, let T_s and T_c denote the expected transmission time of an arbitrary packet in the network and the expected duration of an arbitrary collision, respectively. As described in Section III-B, a transmission attempt may result in a collision, and multiple collisions may be observed in the network before a packet is successfully transmitted. Then, the average service time for a packet in the network, $1/\mu$, is given by

$$\frac{1}{\mu} = T_s P(AQE) + [T_s + \text{Backoff time} + \text{Collision time}]\, P(AQNE).$$

Let p_c denote the conditional probability that an arbitrary packet transmission in the network experiences a collision. Then with probability $(1-p_c)$ there is no collision and the packet is transmitted successfully after its residual backoff. With probability $p_c(1-p_c)$ a packet is transmitted after exactly one collision, and in general, the number of collisions before the transmission is successful has a geometric distribution with parameter p_c. Let T_{RB} denote the expected residual backoff after a collision or a successful transmission. Then, the expression for the expected service time in the network can be written as

$$\begin{aligned}\frac{1}{\mu} &= T_s(1-\rho) + [(1-p_c)(T_s+T_{RB}) \\ &\quad + p_c(1-p_c)(T_s+T_{RB}+T_c+T_{RB}) \\ &\quad + p_c^2(1-p_c)(T_s+T_{RB}+2(T_s+T_{RB})+\cdots \\ &\quad + p_c^{\nu}(1-p_c)(T_s+T_{RB}+i(T_s+T_{RB})+\cdots]\,\rho\end{aligned}$$

where ρ is the utilization of the aggregate queue and thus $Pr[AQE] = 1-\rho$. Simplifying the expression above, we get,

$$\begin{aligned}\frac{1}{\mu} &= T_s + \rho T_{RB} + (1-p_c)\rho(T_c+T_{RB})p_c\left[\sum_{\nu=1}^{\infty}\nu p_c^{\nu-1}\right] \\ &= T_s + \rho T_{RB} + (1-p_c)\rho(T_c+T_{RB})p_c\frac{1}{(1-p_c)^2} \\ &= T_s + \frac{\rho(T_{RB}+p_cT_c)}{1-p_c}. \qquad (16)\end{aligned}$$

In the IEEE 802.11 MAC protocol, packets are discarded after they fail a certain number of retransmission attempts. In the equation above, we have relaxed this rule in order to keep the expressions simple, since in most practical scenarios, this limit is not reached.

The residual backoff time between two transmission attempts is the minimum of the backoff counters of all the nodes who have packets to send. Characterizing the exact distribution of the residual time is intractable since different nodes may be in different stages of their backoff. As an approximation, we note that all nodes that are in backoff would have chosen their backoff counter from a window of at least $[0, CW_{min}-1]$. For n uniformly distributed random variables in the range $[0, CW_{min}-1]$, the average separation between the random variables is $(CW_{min}-1)/(n+1)$. Thus, we approximate the expected residual backoff time as $T_{RB} = (CW_{min}-1)\delta/(n+1)$.

Now, the aggregate packet arrival rate into the network is $\lambda = \sum_{u=1}^{n}\lambda_u$. Then, using $\rho = \lambda/\mu$ in (16), we get

$$\rho = \frac{T_s}{\frac{1}{\lambda} - \frac{T_{RB}+p_cT_c}{1-p_c}}. \qquad (17)$$

Thus the probability that the aggregate queue is empty is given by,

$$p_0 = 1 - \frac{T_s}{\frac{1}{\lambda} - \frac{T_{RB}+p_cT_c}{1-p_c}}. \qquad (18)$$

The conditional collision probability p_c in the expression above is the probability that an arbitrary transmission in the network experiences a collision. This probability is given by the weighted average of the collision probabilities at the individual nodes and can be expressed as

$$p_c = \frac{\sum_{u=1}^{n}\lambda_u p_u}{2\sum_{u=1}^{n}\lambda_u} \qquad (19)$$

where the factor 2 in the denominator corresponds to the first degree approximation that only two nodes are involved in a collision.

To complete the model, we note that the packet sizes may vary across nodes and thus the packet transmission times and duration of collisions may also vary. The expected transmission time of an arbitrary packet in the network, T_s, is then given by

$$T_s = \frac{\sum_{u=1}^{n}\lambda_u T_{s,u}}{\sum_{u=1}^{n}\lambda_u}. \qquad (20)$$

For simplicity, the expression above assumes that there are either no losses in the network, or that all nodes have the same loss rates. This approximation does not cause significant errors since we are considering a stable system where the overall arrival rate into the system is smaller than the service rate. To evaluate the duration of an arbitrary collision in the network, we note that in a co-located network (where all nodes are in each other's transmission range) as assumed in this paper, collisions occur when two or more nodes transmit at the same time (or within a backoff slot duration). The collision ends (i.e. the channel becomes idle) when the node with the longer transmission time ends its transmission. Therefore in the aggregate queue, the duration of a collision is the largest transmission time among the packets involved in collision. Given that a packet from node u experiences a collision, the probability that node v is the other node involved in the collision is $\frac{\lambda_v}{\sum_{\alpha=1,\alpha\neq u}^{n}\lambda_\alpha}$. The expected length of a collision involving node u is then given by

$$T_{c,u} = \left[\frac{1}{\sum_{\alpha=1,\alpha\neq u}^{n}\lambda_\alpha}\right]\sum_{v=1,v\neq u}^{n}\lambda_v \max\left\{T_{s,u},T_{s,v}\right\}. \quad (21)$$

To obtain the expected duration of an arbitrary collision in the network, T_c, we first note that the expected number of collisions per unit time experienced by node u is given by

$$C_u = \lambda_u \frac{p_u}{1-p_u}$$

where p_u can be obtained using (11) and (13). Again, the expression above assumes that the overall system is stable. The expected duration of a collision is then given by

$$T_c = \left[\frac{1}{\sum_{v=1}^{n} C_v}\right]\sum_{u=1}^{n} C_u T_{c,u}. \quad (22)$$

D. Duration of White Spaces

Using the queueing models developed in Sections III-B and III-C, we now develop a model for the duration of white spaces in the Wi-Fi network. The white spaces in the Wi-Fi network correspond to the instances when the aggregate queue is empty. Let $F_{WS}(t) = P(WS \leq t)$, $t \geq 0$, denote the cumulative distribution function (CDF) of the duration of the white spaces. To obtain this distribution, we first define the CDF of the duration of the white spaces conditioned on the state of the arrival process. We define $u^*(t,j|i)$ as the probability that the idle period of the $BMAP/G/1/nK$ queue is less than t and the phase of the arrival process at the start of subsequent busy period is j, given that the phase of the arrival process at the end of the preceding busy period was i. Thus,

$$u^*(t,j|i) = P(WS < t, j|i) \qquad \forall\ i,j \in 1,2,\cdots,m^n. \quad (23)$$

The conditional CDFs $u^*(t,j|i)$, $1 \leq i,j \leq m^n$, are then used to form a $m^n \times m^n$ matrix $U^*(t)$. The transform of $U^*(t)$ is given by [20]:

$$\mathrm{U}^*(s) = [sI - D(0)]^{-1}(D(1) - D(0)) \quad (24)$$

where I is an $m^n \times m^n$ identity matrix. From (3), we have, $D(0) = D_0$ and $D(1) - D(0) = D_1 + D_2 + D_3 + \cdots$. Numerical methods such as the procedure presented in [21] may be used to invert the transform in (24) and obtain the conditional probabilities $u^*(t,j|i)$. The CDF of the duration of white spaces is then given by

$$P(WS < t) = U^*(t)e\pi \quad (25)$$

where e is an unit column vector. Interestingly, from (25) we observe that the duration of white spaces is independent of the service time distribution. This in turn implies that the duration of the white spaces does not depend on the packet lengths or the transmission rate. An intuitive explanation for this is that a white space starts when there is no packet in the queue, and when the white space will end is independent of the service time as no packet is being served. The white space ends when the next packet arrival occurs which is determined by the arrival process. The arrival process is independent of the packet length and transmission rate and thus so is the duration of white spaces. However, the time instants when a white space starts is dependent on the service time since a white space starts when all the packets are served. Hence, the number of white spaces starting in an unit of time is dependent on how fast packets are served (as can be see in (28)) but once a white space starts, the time instant when it will end is dependent only on the arrival process.

E. Expected Duration of White Spaces

Using the derivative of (24), the matrix $E[U^*(t)]$ of conditional expected durations of the white spaces is given by

$$E[U^*(t)] = (-1)\left.\frac{d(U^*(s))}{ds}\right|_{s=0} = ((-D_0)^{-1})^2(D(1)-D_0). \quad (26)$$

Unconditioning using the steady state probabilities of the arrival process, the expected duration of a white space, $E[WS]$, is given by

$$E[WS] = E[U^*(t)]e\pi = ((-D_0)^{-1})^2(D(1) - D_0)e\pi. \quad (27)$$

Let N_{WS} denote the average number of white spaces in unit time. Since p_0 denotes the probability that the aggregate queue is empty, the fraction of time the medium is idle in any interval is also p_0. Then the expected number of white spaces in unit time can be obtained by dividing p_0 by $E[WS]$. Thus

$$\begin{aligned} N_{WS} &= \frac{p_0}{((-D_0)^{-1})^2(D(1)-D_0)e\pi} \\ &= \left[1 - \frac{T_s}{\frac{1}{\lambda} - \frac{T_{RB}+p_cT_c}{1-p_c}}\right]\frac{1}{((-D_0)^{-1})^2(D(1)-D_0)e\pi}. \end{aligned} \quad (28)$$

F. Expected Length of Busy Periods

While the duration and frequency of white spaces are important indicators of the feasibility of opportunistic communications, another important factor is the expected length of busy periods in the Wi-Fi network. The busy period durations represent the time between successive periods for opportunistic communications and thus affect the delays experienced by M2M communications. Let N_{BP} denote the number of busy periods in an interval of unit time. Since each idle period is followed by a busy period and vice versa, on an average, the number of busy periods in any interval is equal to number of idle periods. Thus we have

$$N_{BP} = N_{WS}. \quad (29)$$

Let $E[BP]$ denote the average duration of a busy period. Since there are N_{BP} busy periods on average in an unit of time, and the fraction of time the queue is busy is $\rho = 1 - p_0$, $E[BP]$ is given by

$$E[BP] = \frac{1-p_0}{N_{WS}} = \left(\frac{T_s}{\frac{1}{\lambda} - \frac{T_{RB}+p_cT_c}{1-p_c}}\right)[N_{WS}]^{-1}. \quad (30)$$

IV. Simulation Results

This section presents simulation results to verify the model presented in the previous section and uses the results to provide insights into the white spaces in Wi-Fi networks. The simulations were performed using the NS3 simulation tool. The topology considered in the simulations considers a Wi-Fi network with one AP and four users, using the IEEE 802.11g protocol with a transmission rate of $R = 18$ Mbps. Such a scenario reflects typical homes and some office environments. Each simulation was run for 3600 seconds, and each result is averaged over 5 runs.

The traffic at each Wi-Fi node in the network is generated as per a 2-state BMAP. Simulations were conducted for two scenarios. In the first scenario, denoted by A1, the uplink and downlink traffic have the same packet size of 1500 bytes, and the downlink arrival rate is twice the uplink rate. In the second scenario (A2), the downlink packet size is 1500 bytes but the uplink packet size is 500 bytes and the downlink packet arrival rate is equal to that of the uplink. For both scenarios, the traffic arrival rate is varied (while maintaining the uplink to downlink ratio) to create scenarios with a range of traffic loads. Note that for both scenarios, the data transmitted in the downlink is more than that in the uplink, reflecting typical usage scenarios. The two scenarios illustrate the impact of packet sizes and traffic arrival rates on the white spaces, while maintaining the asymmetry in the uplink and downlink traffic.

To evaluate the accuracy of the $BMAP/G/1/nK$ 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, as given by (18). Figures 1 and 2 show the simulation and analytic results for p_0 for scenarios A1 and A2, respectively, for various values of the overall traffic intensity. We note that there is a close match between the analytic and simulation results. We also compare the analytic expression for the average service time as given in (16) with those obtained using simulations and Figure 3 shows the results. The average service time of packets in scenario A2 is smaller than those in scenario A1 because of smaller uplink packets. We note the close match in the simulation and analytic results, demonstrating the ability of the proposed model to characterize the impact of collisions and backoffs on the service times.

The CDF of the duration of white spaces, for various values of ρ, is shown in Figure 4 for scenario A1. As expected, white spaces of longer duration occur more frequently when the network utilization (or packet arrival rate) is lower. For example, in Figure 4, the probability that the duration of a white space is less than 5 ms is 0.4 when $\rho = 0.1$ and is 0.98 when $\rho = 0.8$ (which also shows that for moderate to low loads, a large fraction of the white spaces are longer than 5 ms). Figure 5 shows the CDF of the duration of white spaces for the second scenario (A2). We observe that the distribution curves are steeper in this case as compared to Figure 4. This is due to the fact that for the same overall network utilization, there are more uplink packets in scenario A2 as compared to A1. A larger number of packets results in more frequent transmissions, which in turn reduces the likelihood of longer white spaces.

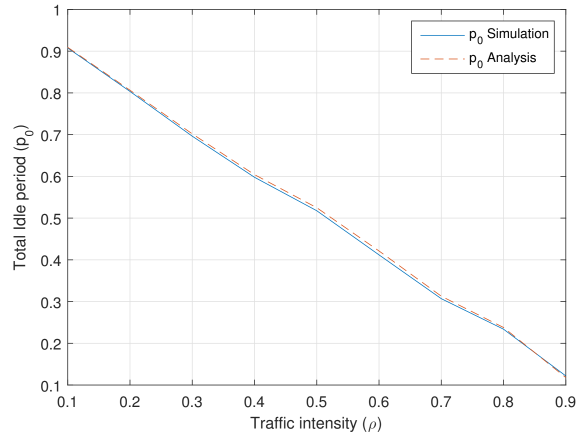

Fig. 1. Comparison of values of p_0 obtained through simulations and the proposed model for scenario A1.

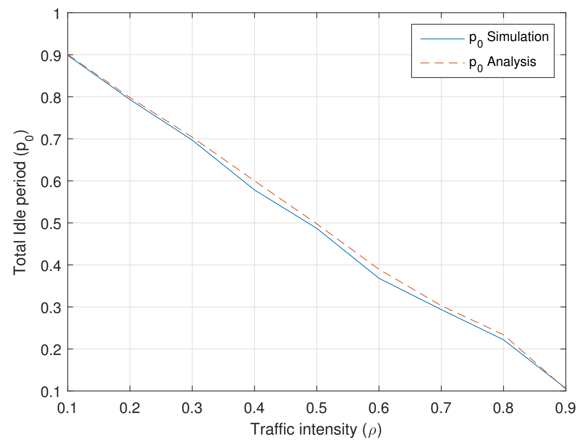

Fig. 2. Comparison of values of p_0 obtained through simulations and the proposed model for scenario A2.

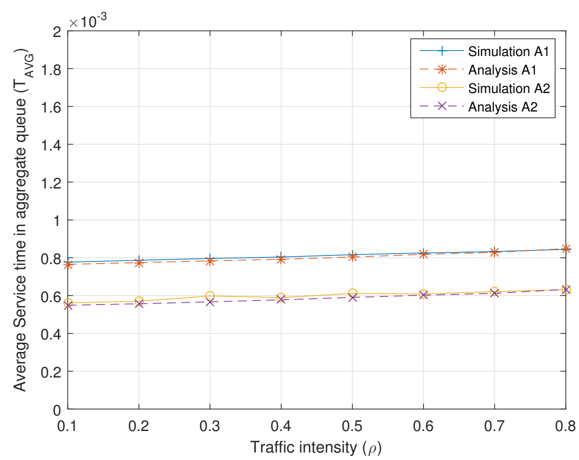

Fig. 3. Average service time experienced by a packet in the aggregate queue.

To evaluate the feasibility of opportunistic M2M communications using white spaces in Wi-Fi networks, next we consider the likelihood of white spaces greater than 1 ms, keeping in mind the small packet sizes and data rates of typical M2M

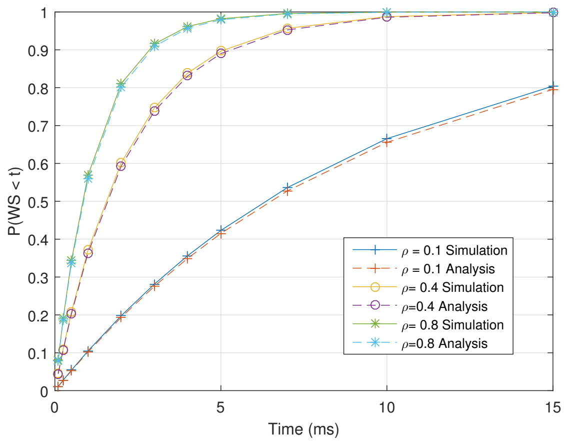

Fig. 4. CDF of the duration of white spaces (WS) for scenario A1.

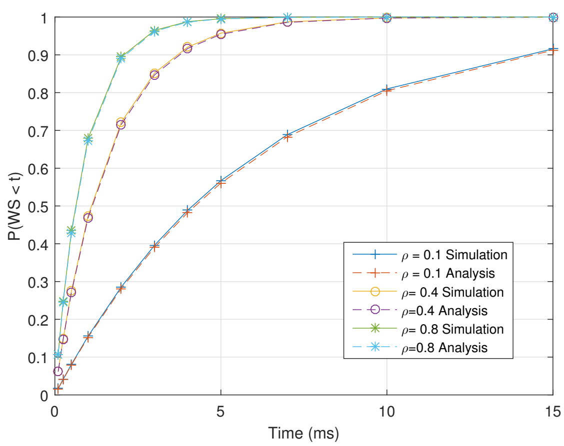

Fig. 5. CDF of the duration of white spaces (WS) for scenario A2.

devices (e.g., it takes 0.78 ms to transmit a 50 byte packet at 512 kbps). Figure 6 shows $P(WS > 1 \text{ ms})$ as a function of ρ for scenarios A1 and A2. It can be seen that even at high loads of $\rho = 0.8$, 32% of the white spaces are longer than 1 ms in scenario A2. On the other hand, $P(WS > 1 \text{ ms})$ is 43% at $\rho = 0.8$ in scenario A1. The reason behind this difference is that for the same ρ, many small sized packets (in scenario A2) interrupt the white spaces more frequently than fewer larger sized packets (in scenario A1). Thus, the probability that the duration of a white space is greater than 1 ms is lower for smaller size packets for the same overall traffic intensity. This can also be noted from Figure 7 which shows the average duration of white spaces, D_{WS}, for different values of ρ. As expected, the duration of white spaces decreases with increasing traffic. The differences between scenarios A1 and A2 can be attributed to the larger number of uplink packets which divide the white spaces more often in case of scenario A2.

In order to accommodate a given number of M2M nodes, there should be sufficient number of white spaces for the M2M nodes to transmit data. Figure 8 shows the average number of white spaces per second as a function of ρ. The

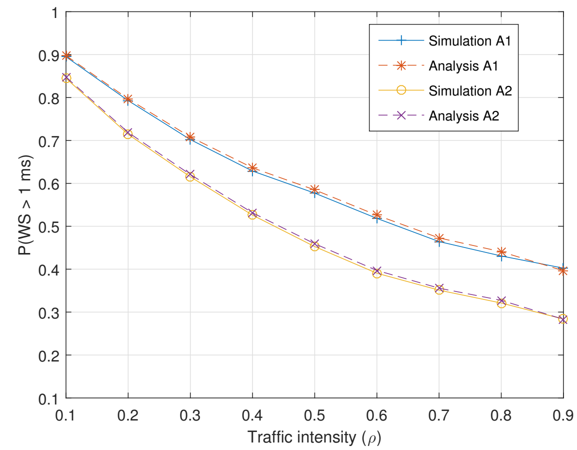

Fig. 6. $P(WS \geq 1 \text{ ms})$ for different values of ρ.

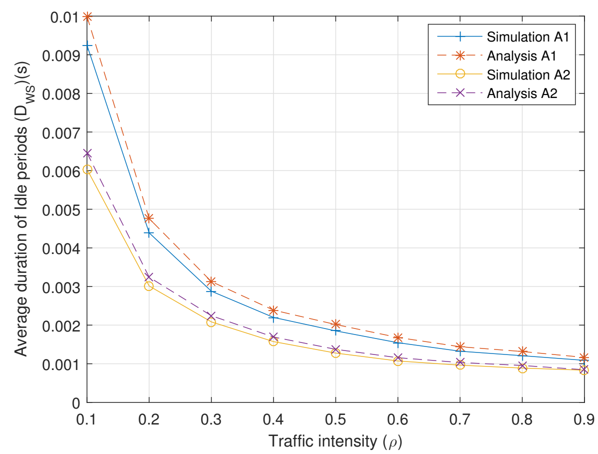

Fig. 7. Average duration of white spaces for different values of ρ.

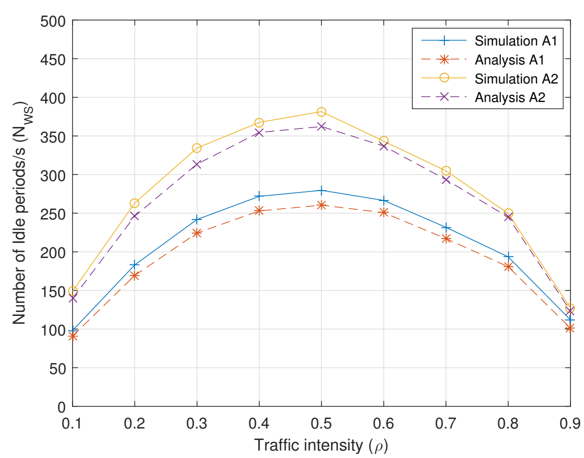

Fig. 8. Average number of white spaces per unit time for different values of ρ.

number of white spaces per unit time first increases as the network utilization increases, before decreasing again. This

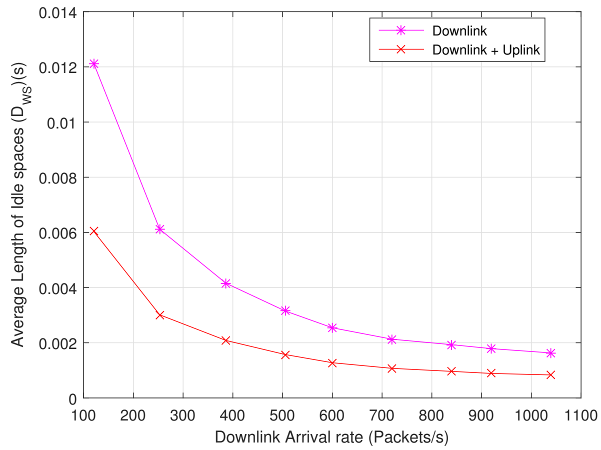

Fig. 9. Comparison of average duration of white spaces (D_{WS}) with only downlink traffic and with both downlink and uplink traffic.

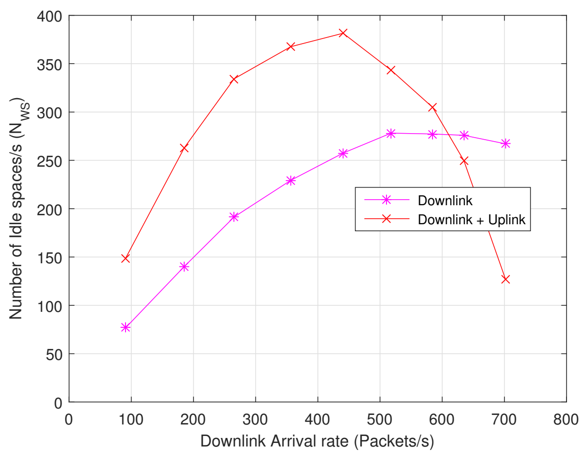

Fig. 10. Comparison of average number of white spaces (N_{WS}) with only downlink traffic and with both downlink and uplink traffic.

occurs because when the load is low, the idle periods in the Wi-Fi network are longer, but the number of idle periods is small. As the traffic load increases, the idle periods are interrupted more often by frequent transmissions of Wi-Fi packets. This decreases the average duration of white spaces but the number of white spaces increases. This also explains why the number of white spaces is larger in scenario A2 which has a larger number of uplink packets. However, as the load keeps increasing, the Wi-Fi network stays busy for longer periods of time. This in turn decreases both the average duration and number of white spaces. However, even at high loads, white spaces of sufficiently long duration occur frequently enough to support opportunistic M2M communications. For example, when $\rho = 0.9$ in scenario A1, the average duration of a white space is 1.01 ms and the average number of white spaces is 110 per second.

To determine the effect of the addition of uplink traffic on the white spaces and to highlight the importance of the model presented in this paper over that proposed in [12] (with only downlink traffic), we also conducted simulations in which only downlink traffic was present. These results are compared with those from scenario A2, and the simulations for both cases has an equal number of downlink packets while scenario A2 also had (the same number of) uplink packets. Figure 9 shows the average duration of white spaces for the case with only downlink traffic, and where both downlink and uplink traffic are present. The x-axis of the figure shows the number of downlink packets per second. As can be seen from Figure 9, at low loads, the average duration of white spaces is almost halved in the presence of uplink traffic. This is because at low loads, a majority of the packets find the MAC layer queue empty and the channel idle on arrival, and are transmitted immediately without any waiting in the queue. Thus the transmission of most packets results in the termination of an ongoing idle period. Since there are twice as many packets in scenario A2 as compared to the scenario with only downlink traffic, there are twice as many interruptions. Thus the average duration of white spaces is approximately halved and the number of white spaces per unit time is doubled, as shown in Figure 10. However, as the load increases, an increasing number of packets arrive at busy queues and the average duration of white spaces reduces. Also, since the overall number of packets is larger in scenario A2, the load is higher as compared to the scenario with only downlink traffic. Consequently, the number of idle periods starts decreasing at a lower downlink packet arrival rate as compared to the scenario with only downlink traffic. From Figures 9 and 10 we can see that the addition of uplink traffic can significantly affect the characteristics of white spaces.

A. Discussion

The model proposed in this paper and its results show that opportunistic communication is a viable option for supporting M2M devices. There is some initial work in this direction and protocols have been proposed that, to various degrees, exploit silent periods in Wi-Fi networks for transferring M2M data. In the protocol proposed in [14], the Wi-Fi AP sends a CTS packet to block Wi-Fi nodes from transmitting (upto 32 ms), in order to allow ZigBee based devices to communicate with lower bit error rates. Similarly, in the protocol proposed in [13], ZigBee devices periodically mute Wi-Fi nodes by broadcasting fake-PHY preamble headers. However, these are not protocols that utilize naturally occurring silent periods in the Wi-Fi network. Instead, Wi-Fi devices are forcibly kept silent and this may significantly increase their packet delays. The protocol in [10] uses predictions of the duration of white spaces to determine the frame size of ZigBee transmissions, with the objective of ensuring that ZigBee transmissions complete within the white space and thus avoid interference with Wi-Fi transmissions.

The significance of the proposed model in the context of opportunistic M2M communications is two-fold. First, it provides a means for validating the feasibility of opportunistic M2M communication for a given Wi-Fi network scenario. Second, the characterization of the white spaces provided by the model may be used in real time to facilitate the operation and scheduling of opportunistic M2M communications, while maintaining a desired level of service for the Wi-Fi users. For example, the CDF of the duration of white spaces may be used to determine the duration for which M2M devices may transmit when a white space starts, while keeping the likelihood that the transmission will not stifle a new Wi-Fi packet below a desired threshold. The development of such protocols is beyond the scope of this paper but present an interesting avenue for exploration.

Finally, we note that a number of other alternatives for M2M communication in the unlicensed band exist or are being developed, such as IEEE 802.11ah, ZigBee, and Bluetooth 4.0. In contrast to the network model considered in this paper, these protocols treat M2M devices on par with other users in the network. Consequently, the network performance observed by the other users is directly impacted by the M2M data transmissions. In scenarios where it is desired to provide a separation in the services provided to M2M devices and other users (e.g. in a home with human users), opportunistic communications provide a viable alternative.

V. Conclusion

This paper addressed the problem of evaluating the feasibility of opportunistic M2M communications in the license-free ISM bands. The paper presented an analytic model to evaluate the feasibility of a scenario where Wi-Fi devices are the primary users of the spectrum and M2M devices exploit the idle periods in the Wi-Fi network to transmit their data. Using a $BMAP/G/1/nK$ queue to model the overall Wi-Fi network, we characterized the distribution of the duration of white spaces and their frequency. Our results show that white spaces occur frequently and are sufficiently long to support opportunistic M2M communications.

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