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Per-user service model for opportunistic scheduling scheme over fading channels

Mehrdad Dianati[1*,†], Rahim Tafazolli[1], Xuemin Shen[2] and Kshirasagar Naik[2]

[1]*Department of Electronics and Electrical Engineering, University of Surrey, Guildford, Surrey GU2 7XH, U.K.*
[2]*Department of Electrical and Computer Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada*

Summary

In this paper, we propose a finite-state Markov model for per-user service of an opportunistic scheduling scheme over Rayleigh fading channels, where a single base station serves an arbitrary number of users. By approximating the power gain of Rayleigh fading channels as finite-state Markov processes, we develop an algorithm to obtain dynamic stochastic model of the transmission service, received by an individual user for a saturated scenario, where user data queues are highly loaded. The proposed analytical model is a finite-state Markov process. We provide a comprehensive comparison between the predicted results by the proposed analytical model and the simulation results, which demonstrate a high degree of match between the two sets. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: opportunistic scheduling; performance analysis; radio resource allocation

1. Introduction

Effective radio resource management in the last-mile wireless access networks can provide Quality of Service (QoS) for users and increase the revenue for network operators. As shown in Figure 1, a typical radio resource management system a wireless access network includes three modules for: (1) access control to regulate the incoming traffic according the per-user service level agreement of the admitted users, (2) admission control to avoid system overload, and (3) scheduling in order to dynamically share the network resources among admitted users. Transmission scheduling is an efficient technique for dynamic resource sharing among multiple users, i.e., dynamic resource allocation. In the context of this paper, a single resource can be the entire bandwidth of a channel in single carrier systems, or an individual subcarrier in multi-carrier systems, e.g., OFDMA. In either case, a single unit of interest can be abstracted as a single base station that schedules transmission of data to multiple users. In the presence of partial

*Correspondence to: Mehrdad Dianati, Department of Electronics and Electrical Engineering, University of Surrey, Guildford, Surrey GU2 7XH, U.K.
†E-mail: m.dianati@surrey.ac.uk

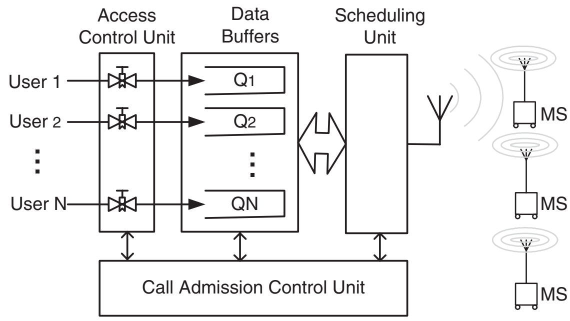

Fig. 1. Resource management system.

Channel State Information (CSI), it has been shown in References [1,2] that the optimal scheduling strategy in order to maximize the total bandwidth utilization is to transmit to a single user with the best channel quality in each scheduling epoch (i.e., time slot). This can be considered as an *opportunistic service discipline* that relies on the partial CSI provided by the users through feedback channels. Opportunistic scheduling with Adaptive Modulation and Coding (AMC) are widely proposed for modern wireless systems [3–10]. Developing analytical models for opportunistic scheduling thus is a practically useful and theoretically challenging problem. Such models can be used in performance analysis of resource management and implementation of effective resource management policies. For example, designing of an efficient admission control scheme requires a reliable model of the underlying scheduling scheme.

Considering both the impacts of random fluctuations of the wireless channels and the scheduling scheme makes the analytical approaches significantly difficult, which has been partially studied in the recent years. In Reference [11], an algorithm for computing the probability mass function of system throughput, per-flow throughput, and inter-success delay of opportunistic scheduling for both uncorrelated and correlated wireless channels are given. In References [12] and [13], a vacation-based queuing analysis for Bernoulli arrival is used to obtain delay distribution where wireless channels are independent and identically distributed finite-state Markov processes. In Reference [14], a model for per-user throughput of opportunistic scheduling scheme has been proposed.

Different from the aforementioned studies, in this paper, we model the stochastic dynamics of a single user's service which can be used to conduct a wide variety of performance studies. In our approach, we consider a system with a single base station and an arbitrary number of users. Transmission scheduling from the base station to the mobile users is decided by an opportunistic scheduler. As a preliminary step, we derive a finite-state Markov model for the fading channels, extending a simple 2-state Markov model in Reference [15]. We proceed by dividing the users into a *tagged user*, whose per-user service model is to be obtained, and the rest of users, namely, competing users. Then rest of the analysis, in order to obtain the per-user service model, is performed in two steps. In the first step, the set of competing users is abstracted by a single competing user, namely, the *tagged user*. The channel power gain of the super user is also modeled by a finite-state Markov model. In the second step, we consider an opportunistic scheduling scheme between the tagged user and the super user. The outcome of the analysis of the reduced model gives us a dynamic stochastic model for the transmission service, received by the tagged user, namely, *per-user dynamic service model*. Several simulation cases as well as the summary of comprehensive simulations are given to show the accuracy of the proposed models. We also give an example demonstrating the application of the proposed model for computing the per-user and the total throughput of an opportunistic scheduler.

The rest of this paper is organized as follows. In Section 2, we present the system model. The analytical model is proposed in Section 3. In Section 4, we give the comparison between the analytical and simulation results and a sample application of the proposed model. The concluding remarks are given in Section 5.

2. System Model

We consider opportunistic scheduling from a single base station with single antenna to multiple users, each with a single antenna, as shown in Figure 2. A quasi static Rayleigh flat fading model is assumed for the wireless channels, where the SINR value at a mobile station is a random variable that remains constant for an entire duration of a time slot. We consider a scenario where users have statistically identical and ergodic channels during the time period of the analysis. During this period shadowing and path loss are considered to be constant. It is widely accepted that such channels can be modeled by a finite-state Markov process [16]. This model approximates the dynamics of the random fluctuations of the wireless channels due to fast fading. In this model, the range of the received SINR by a user is divided into multiple sections. When the signal power is below ζ_i and above ζ_{i-1}, the channel is considered

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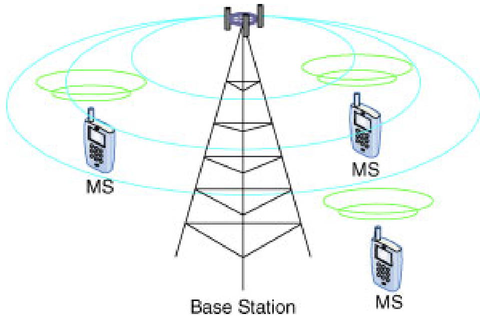

Fig. 2. System model.

in state S_i. The transition probability from state S_i to state S_j in the next time slot is denoted by $p_{i,j}$. The algorithms for computation of transition probabilities are given in Reference [16]. It is also shown that the transition among nonadjacent states can be neglected. Thus, there are only transition among adjacent states, as shown in the figure.

An opportunistic scheduling scheme operates as follows: mobile users estimate their received Signal to Interference and Noise Ratio (SINR) from a pilot signal and report the maximum achievable rates back to the base station through a feedback channel. Comparing the received SINR of different users, the scheduler selects a single user with the highest achievable rate in each time slot. If two or more users have similar maximum achievable rates in a time slot, i.e., a tie scenario, the scheduler may apply a tie breaking policy. A simple and straightforward policy may be a random tie breaking policy that gives equal chance to all users with equal channel qualities. Mapping between the values of SINR and the achievable transmission rates is often obtained from system level simulations. As mentioned, we consider statistically identical channel for users. This implies that the average channel gain for the users are equalized by a proper power allocation scheme. This eliminates the possibility of unfair resource allocation by the scheduler.

In the next section, we explain how the received service of a single user can be modeled in a system specified in this section.

3. Analytical Model

We develop the analytical model in two steps. To obtain the service model of a tagged user, the scheduling problem with multiple users is simplified into a scheduling problem where the tagged user competes with a single super user. The super user combines the competing capability of all users, except the tagged user. The first step is to model the instantaneous achievable rate of the super user by a finite-state Markov process in subsection 3.1. In the second step, the problem is effectively reduced into an scheduling scenario with only two users. The reduced problem then can be solved to obtain the service model of a single user in 3.2. We also give an straightforward extension of a 2-state Markov model for representing the dynamics of the channel of a single user in Appendix A.

3.1. Channel Model of the Super User

Let N be the number of mobile users and $X(t)$ be the channel state of a tagged user in time slot t. Denote by $X_i(t)$, $i = 1, \ldots, N-1$, the state of the channel from the base station to the compteting user i in time slot t. The tagged user wins the competition for transmission in a time slot if $X(t) > \max(X_i(t), \ldots, X_{N-1}(t))$ or when a tie is randomly broken in its favor. This competition policy suggests that the tagged user virtually competes with a super user whose channel state is given by $Z = \max(X_i, \ldots, X_{N-1})$. Thus, we can simplify the analysis by replacing all competing users with a super user whose channel model can be computed from those of the $N-1$ competing users as follows.

We develop an iterative algorithm to obtain the channel model of the super user by gradual combination of the channel models of the $N-1$ competing users. First, we develop an algorithm to combine the channel models of two users. Let $p_{i,j}$ and $q_{i,j}$ be the probability of transition from state S_i to state S_j for users 1 and 2, respectively. Thus,

$$\begin{aligned} p_{i,j} &= \Pr\{X_1(t) = S_j \mid X_1(t-1) = S_i\} \\ q_{i,j} &= \Pr\{X_2(t) = S_j \mid X_2(t-1) = S_i\} \end{aligned} \qquad (1)$$

Denote by $Z(t)$ the channel-state of the combined super node, given by $Z(t) = \max(X_1(t), X_2(t))$. Let $\delta_{i,j}$ be the state transition probability of $Z(t)$, defined as $\delta_{i,j} = \Pr\{Z(t) = S_j | Z(t-1) = S_i\}$. To simplify the expressions, we define the following events.

$$\begin{aligned} S_i(t) &: \{Z(t) = S_i\} \\ S_{i,j}(t) &: \{X_1(t) = S_i, X_2(t) = S_j\} \end{aligned} \qquad (2)$$

Since $Z(t)$ is the maximum of two random processes, $X_1(t)$ and $X_2(t)$, it will less frequently be in lower states. For very small values of $\Pr\{S_i(t-1)\}$, e.g., less than 0.1% of the average state probability of staying in a

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typical state, we can safely eliminate state S_i and reduce the number of states. Alternatively, we can assume that the process will move to the next higher state with a probability close to 1, i.e.,

$$\delta_{i,j} = \begin{cases} 1, & \text{if } j = i+1 \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

and

$$\delta_{j,i} = 0, \text{if } j < i \tag{4}$$

For significant values of $\Pr\{S_i(t-1)\}$, larger than 1% of the average value of the probability of being in any state,

$$\begin{aligned}\delta_{i,j} &= \Pr\{S_j(t)|S_i(t-1)\} \\ &= \Pr\left\{\left[\bigcup_{l=1}^{j-1}\left(S_{j,l}(t) \cup S_{l,j}(t)\right)\right] \cup S_{j,j}(t) \middle| S_i(t-1)\right\}\end{aligned}$$

Since $S_{j,l}(t)$, $S_{l,j}(t)$, and $S_{j,j}(t)$ are mutually exclusive events,

$$\delta_{i,j} = \sum_{l=1}^{j-1}\left[\mu(i,j,l) + \mu(i,l,j)\right] + \mu(i,j,j) \tag{5}$$

where

$$\begin{aligned}\mu(i,m,n) &= \Pr\{S_{m,n}(t)|S_i(t-1)\} \\ &= \frac{\Pr\{S_i(t-1)|S_{m,n}(t)\}\Pr\{S_{m,n}(t)\}}{\Pr\{S_i(t-1)\}}\end{aligned}$$

and

$$\begin{aligned}&\Pr\{S_i(t-1)|S_{m,n}(t)\} \\ &= \Pr\left\{\left[\bigcup_{k=1}^{i-1} S_{i,k}(t-1) \cup S_{k,i}(t)\right] \cup S_{i,i}(t-1) \middle| S_{m,n}(t)\right\} \\ &\Pr\{S_i(t-1)\} \\ &= \Pr\left\{\left[\bigcup_{k=1}^{i-1} S_{i,k}(t-1) \cup S_{k,i}(t)\right] \cup S_{i,i}(t-1)\right\}\end{aligned} \tag{6}$$

Since $S_{i,k}(t)$, $S_{k,i}(t)$, and $S_{i,i}(t)$ are mutually exclusive events,

$$\mu(i,m,n) = \left[\frac{T_1 + T_2}{T_3 + T_4}\right]\Pr\{S_{m,n}(t)\} \tag{7}$$

where

$$\begin{aligned}T_1 &= \sum_{k=1}^{i-1}\left[\Pr\{S_{i,k}(t-1)|S_{m,n}(t)\}\right. \\ &\quad \left.+ \Pr\{S_{k,i}(t-1)|S_{m,n}(t)\}\right], \\ T_2 &= \Pr\{S_{i,i}(t-1)|S_{m,n}(t)\}, \\ T_3 &= \sum_{k=1}^{i-1}\left[\Pr\{S_{i,k}(t-1)\} + \Pr\{S_{k,i}(t-1)\}\right], \\ T_4 &= \Pr\{S_{i,i}(t)\}\end{aligned} \tag{8}$$

Using properties of conditional probabilities,

$$\begin{aligned}&\Pr\{S_{i,k}(t-1)|S_{m,n}(t)\} \\ &\quad = \frac{\Pr\{S_{m,n}(t)|S_{i,k}(t-1)\}\Pr\{S_{i,k}(t-1)\}}{\Pr\{S_{m,n}(t)\}} \\ &\quad = \frac{p_{i,m}q_{k,n}\pi_{i,k}}{\pi_{m,n}}\end{aligned} \tag{9}$$

where

$$\begin{aligned}\pi_{i,k} &= \Pr\{S_{i,k}(t)\} \\ &= \Pr\{X_1(t) = S_i\}\Pr\{X_2(t) = S_k\}\end{aligned} \tag{10}$$

Hence,

$$\begin{aligned}&\mu(i,m,n) \\ &= \frac{p_{i,m}q_{i,n}\pi_{i,i} + \sum_{k=1}^{i-1}(p_{i,m}q_{k,n}\pi_{i,k} + p_{k,m}q_{i,n}\pi_{k,i})}{\pi_{i,i} + \sum_{k=1}^{i-1}(\pi_{i,k} + \pi_{k,i})}\end{aligned} \tag{11}$$

We can extend the procedure for computing the channel model of a super user to an arbitrary number of users by repeating the above algorithm, until all $N-1$ competing users are considered.

3.2. Service Model of a Single User

Next, the problem is reduced to a scheduling problem with two users, where the tagged user competes with a single super user. The reduced scenario can be used to obtain the service model of the tagged user. Let $X(t)$ and $Z(t)$ represent the channel states of the tagged user and the equivalent super user, respectively. Denote by $C(t)$ the service model of the tagged user. $C(t)$ can be modeled by an $(m+1)$-state Markov process, where m is the number of the states of the fading channels.

An extra state of $C(t)$, denoted by S_0, indicates a non-scheduled state, where the tagged user does not win the competition for transmission in time slot t.

First, we define the following notations:

$$\begin{aligned}
&\gamma_{i,j} = \Pr\{C(t) = S_j | C(t-1) = S_i\} \\
&\text{Event } S'_{i,j}(t) : \{X(t) = S_i, Z(t) = S_j\} \\
&\sigma_{i,j} = \Pr\{S'_{i,j}(t)\} \\
&p_{i,j} = \Pr\{X(t) = S_j | X(t-1) = S_i\} \\
&\delta_{i,j} = \Pr\{Z(t) = S_j | Z(t-1) = S_i\}
\end{aligned} \tag{12}$$

To take into account the tie breaking policy, we denote the event that the tagged user wins a tie in state S_i by E_i and the corresponding probability by ϵ_i. We consider a tie-breaking policy that randomly selects one of the users with the highest achievable rate and gives equal chance of winning a tie case to all users. For this policy,

$$\epsilon_i = \sum_{k=1}^{N-1} \frac{1}{k+1} \Pr\{k \text{ users in state } S_i\} \tag{13}$$

$$\Pr\{k \text{ users in state } S_i\} = \binom{N-1}{k} \pi_i^k (1-\pi_i)^{(N-1-k)} \tag{14}$$

where π_i is the probability that the channel state of a single user is in state S_i. Plugging Equation (14) into Equation (13),

$$\epsilon_i = \sum_{k=1}^{N-1} \frac{1}{k+1} \binom{N-1}{k} \pi_i^k (1-\pi_i)^{(N-1-k)} \tag{15}$$

Next, we compute $\gamma_{i,j}$. For non-significant values of $\Pr\{C(t-1) = S_i\}$, i.e., less than 1% of the average probability of being in any state,

$$\gamma_{i,j} = \begin{cases} 1, & \text{if } j = 0 \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

For significant values of $\Pr\{C(t-1) = S_i\}$, we break down the problem into three separate cases: $i, j \neq 0$; $i = 0, j \neq 0$; and $i \neq 0, j = 0$. It is obvious that the case $i = 0, j = 0$ can be obtained from the basic property of a transition probability matrix, where the sum of each row is one.

For $i, j \neq 0$, from definition of $\gamma_{i,j}$ in Equation (12),

$$\gamma_{i,j} = \Pr\left\{ \left[\left[S'_{j,j}(t) \cap E_j \right] \bigcup_{k=1}^{j-1} S'_{j,k}(t) \right] \middle| C(t-1) = S_i \right\} \tag{17}$$

The right hand side of Equation (17) is the union of mutually exclusive events. Thus

$$\gamma_{i,j} = \underbrace{\Pr\{S'_{j,j}(t) \cap E_j | C(t-1) = S_i\}}_{\mathbf{A}} + \sum_{k=1}^{j-1} \underbrace{\Pr\{S'_{j,k}(t) | C(t-1) = S_i\}}_{\mathbf{B}} \tag{18}$$

Term $\mathbf{A}$ in Equation (18) is given by

$$\begin{aligned}
\mathbf{A} &= \Pr\left\{ S'_{j,j}(t) \cap E_j \middle| \left[S'_{i,i}(t-1) \cap E_i \right] \cup \bigcup_{l=1}^{i-1} S'_{i,l}(t-1) \right\} \\
&= \frac{\mathbf{A_1} + \mathbf{A_2}}{\mathbf{A_3}}
\end{aligned} \tag{19}$$

where

$$\begin{aligned}
\mathbf{A_1} &= \sum_{l=1}^{i-1} \Pr\{S'_{j,j}(t) \cap E_j | S'_{i,l}(t-1)\} \Pr\{S'_{i,l}(t-1)\}, \\
\mathbf{A_2} &= \Pr\{S'_{j,j}(t) \cap E_j | S'_{i,i}(t-1) \cap E_i\} \\
&\quad \times \Pr\{S'_{i,i}(t-1) \cap E_i\}, \\
\mathbf{A_3} &= \Pr\left\{ \left[S'_{i,i}(t-1) \cap E_i \right] \cup \left[\bigcup_{l=1}^{i-1} S'_{i,l}(t-1) \right] \right\}
\end{aligned} \tag{20}$$

Given that

$$\begin{aligned}
&\Pr\{S'_{j,j}(t) \cap E_j | S'_{i,l}(t-1)\} \\
&\quad = \frac{\Pr\{E_j | S'_{j,j}(t) \cap S'_{i,l}(t-1)\} \Pr\{S'_{j,j}(t) \cap S'_{i,l}(t-1)\}}{\Pr\{S'_{i,l}(t-1)\}} \\
&\quad = \epsilon_j p_{i,j} \delta_{l,j}
\end{aligned} \tag{21}$$

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and

$$\begin{aligned}&\Pr\{S'_{j,j}(t)\cap\epsilon(t)=1|S'_{i,i}(t-1)\cap E_i\}\\&\quad=\frac{\Pr\{E_j\cap E_i|S'_{j,j}(t)\cap S'_{i,i}(t-1)\}}{\Pr\{S'_{i,i}(t-1)\cap E_i\}}\\&\qquad\times\Pr\{S'_{j,j}(t)\cap S'_{i,i}(t-1)\}\\&\quad=\epsilon_j p_{i,j}\delta_{i,j}\end{aligned}\tag{22}$$

Using Equations (20)–(22), we can rewrite Equation (19) as follows.

$$\mathbf{A}=\frac{\epsilon_j p_{i,j}\delta_{i,j}\epsilon_i\sigma_{i,i}+\sum_{l=1}^{i-1}\epsilon_j p_{i,j}\delta_{l,j}\sigma_{i,l}}{\epsilon_i\sigma_{i,i}+\sum_{l=1}^{i-1}\sigma_{i,l}}\tag{23}$$

Term $\mathbf{B}$ in Equation (18) can be expanded as

$$\begin{aligned}\mathbf{B}&=\Pr\left\{S'_{j,k}(t)\middle|\bigcup_{l=1}^{i-1}S'_{i,l}(t-1)\cup[S'_{i,i}(t-1)\cap E_i]\right\}\\&=\frac{\mathbf{B_1}+\mathbf{B_2}}{\mathbf{B_3}}\end{aligned}\tag{24}$$

where

$$\begin{aligned}\mathbf{B_1}&=\sum_{l=1}^{i-1}\Pr\left\{S_{j,k}(t)\middle|S_{i,l}(t-1)\right\}\Pr\{S'_{i,l}(t-1)\}\\&=\sum_{l=1}^{i-1}p_{i,j}\delta_{l,k}\sigma_{i,l}\\\mathbf{B_2}&=\Pr\left\{S'_{j,k}(t)\middle|S'_{i,i}(t-1)\cap E_i\right\}\\&\quad\times\Pr\{S'_{i,i}(t-1)\cap E_i\}\\&=p_{i,j}\delta_{i,k}\epsilon_i\sigma_{i,i},\\\mathbf{B_3}&=\epsilon_i\sigma_{i,i}+\sum_{l=1}^{i-1}\sigma_{i,l}\end{aligned}\tag{25}$$

Hence

$$\mathbf{B}=\frac{p_{i,j}\delta_{i,k}\epsilon_i\sigma_{i,i}+\sum_{l=1}^{i-1}p_{i,j}\delta_{l,k}\sigma_{i,l}}{\epsilon_i\sigma_{i,i}+\sum_{l=1}^{i-1}\sigma_{i,l}}\tag{26}$$

For $i=0$ and $j\neq 0$, referring to Equation (12),

$$\gamma_{0,j}=\Pr\{C(t)=S_j|C(t-1)=S_0\}\tag{27}$$

For non-significant values of $\Pr\{C(t-1)=S_0\}$,

$$\gamma_{0,j}=\begin{cases}1, & \text{if } j=0\\0, & \text{otherwise}\end{cases}\tag{28}$$

For significant values of $\Pr\{C(t-1)=S_0\}$,

$$\begin{aligned}\gamma_{0,j}&=\Pr\left\{\left[\bigcup_{k=1}^{j-1}S'_{j,k}\right]\cup[S'_{j,j}\cap E_j]\middle|C(t-1)=S_0\right\}\\&=\sum_{k=1}^{j-1}\underbrace{\Pr\{S'_{j,k}(t)|C(t-1)=S_0\}}_{\mathbf{D}}\\&\quad+\underbrace{\Pr\{S'_{j,j}(t)\cap E_j|C(t-1)=S_0\}}_{\mathbf{F}}\end{aligned}\tag{29}$$

Term $\mathbf{D}$ in Equation (29) is given by

$$\begin{aligned}\mathbf{D}&=\Pr\left\{S'_{j,k}(t)\middle|\left[\bigcup_{l=1}^{m}\bigcup_{n=1}^{l-1}S'_{n,l}(t-1)\right]\right.\\&\qquad\left.\times\cup\left[\bigcup_{l=1}^{m}\left[S'_{l,l}(t-1)\cap\bar{E}_l\right]\right]\right\}\\&=\frac{\mathbf{D_1}+\mathbf{D_2}}{\mathbf{D_3}}\end{aligned}\tag{30}$$

where

$$\begin{aligned}\mathbf{D_1}&=\sum_{l=1}^{m}\sum_{n=1}^{l-1}\Pr\{S'_{j,k}(t)|S'_{n,l}(t-1)\}\Pr\{S'_{n,l}(t-1)\}\\&=\sum_{l=1}^{m}\sum_{n=1}^{l-1}p_{n,j}\delta_{l,k}\sigma_{n,l},\\\mathbf{D_2}&=\sum_{l=1}^{m}\Pr\{S'_{j,k}(t)|S'_{l,l}(t-1)\cap\bar{E}_l\}\\&\quad\times\Pr\{S'_{l,l}(t-1)\cap\bar{E}_l\}\\&=\sum_{l=1}^{m}p_{l,j}\delta_{l,k}(1-\epsilon_l)\sigma_{l,l}\\\mathbf{D_3}&=\Pr\left\{\left[\bigcup_{l=1}^{m}\bigcup_{n=1}^{l-1}S'_{n,l}(t-1)\right]\right.\\&\qquad\left.\times\cup\left[\bigcup_{l=1}^{m}\left[S'_{l,l}(t-1)\cap\bar{E}_l\right]\right]\right\}\end{aligned}$$

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$$= \sum_{l=1}^{m}\sum_{n=1}^{l-1}\sigma_{n,l} + \sum_{l=1}^{m}(1-\epsilon_l)\sigma_{l,l} \tag{31}$$

Thus

$$\mathbf{D} = \frac{\sum_{l=1}^{m}\sum_{n=1}^{l-1} p_{n,j}\delta_{l,k}\sigma_{n,l} + \sum_{l=1}^{m} p_{l,j}\delta_{l,k}(1-\epsilon_l)\sigma_{l,l}}{\sum_{l=1}^{m}\sum_{n=1}^{l-1}\sigma_{n,l} + \sum_{l=1}^{m}(1-\epsilon_l)\sigma_{l,l}} \tag{32}$$

Term $\mathbf{F}$ in Equation (29) can be written as

$$\begin{aligned}\mathbf{F} &= \Pr\left\{ S'_{j,j}(t)\cap E_j \,\middle|\, \left[\bigcup_{l=1}^{m}\bigcup_{n=1}^{l-1} S'_{n,l}(t-1)\right] \right.\\ &\qquad \left. \times \cup \left[\bigcup_{l=1}^{m}\left[S'_{l,l}(t-1)\cap \bar{E}_l\right]\right] \right\}\\ &= \frac{\mathbf{F_1}+\mathbf{F_2}}{\mathbf{F_3}}\end{aligned} \tag{33}$$

where

$$\begin{aligned}\mathbf{F_1} &= \sum_{l=1}^{m}\sum_{n=1}^{l-1}\Pr\{S'_{j,j}(t)\cap E_j | S'_{n,l}(t-1)\}\Pr\{S'_{n,l}(t-1)\}\\ &= \sum_{l=1}^{m}\sum_{n=1}^{l-1} p_{n,j}\delta_{l,j}\sigma_{n,l}\epsilon_j,\\ \mathbf{F_2} &= \sum_{l=1}^{m}\Pr\{S'_{j,j}(t)\cap E_j | S'_{l,l}(t-1)\cap \bar{E}_l\}\\ &\qquad \Pr\{S'_{l,l}(t-1)\cap \bar{E}_l\}\\ &= \sum_{l=1}^{m} p_{l,j}\delta_{l,j}\epsilon_j(1-\epsilon_l)\sigma_{l,l}\\ \mathbf{F_3} &= D_3\end{aligned} \tag{34}$$

Hence

$$\mathbf{F} = \frac{\sum_{l=1}^{m}\sum_{n=1}^{l-1} p_{n,j}\delta_{l,j}\sigma_{n,l}\epsilon_j + \sum_{l=1}^{m} p_{l,j}\delta_{l,j}\epsilon_j(1-\epsilon_l)\sigma_{l,l}}{\sum_{l=1}^{m}\sum_{n=1}^{l-1}\sigma_{n,l} + \sum_{l=1}^{m}(1-\epsilon_l)\sigma_{l,l}} \tag{35}$$

For $i \neq 0$ and $j = 0$, referring to the basic property of a transition probability matrix, i.e., the sum of each row is equal to 1, $\gamma_{i,0} = 1 - \left[\sum_{j=1}^{m}\gamma_{i,j}\right]$.

Table I. Simulation parameters of the fading channels.

Parameter	Value
Carrier frequency	1900 MHz
Sampling frequency	1000 samples per second
Length of a time slot	1.25 ms

4. Simulations Results

In this section, Monte Carlo simulations are presented to verify the accuracy of the analytical models. We validate different components and steps of the proposed model by varying relevant simulation parameters. We also give an illustrative application of the proposed model to compute the per-user throughput and the total throughput of an opportunistic scheduler.

The simulation scenario includes a single base station with an arbitrary number of users, as described in Section 2. The parameters of flat Rayleigh fading channel simulator are specified in Table I. Channels are generated via filtering of two random Gaussian processes representing the in-phase and quadrature-phase components of fading process. The frequency response of the channel is approximated by an FIR filter. Inverse Fast Fourier Transform (IFFT) and time domain convolution are used to compute the impulse response of channel and its samples, respectively.

Throughout this section, we often compare an analytically computed transition matrix, $\mathbf{P_m}$, with the corresponding simulation result, $\mathbf{P_s}$, for different system settings. Unlike the comparison of scalar values, matrices of arbitrary dimensions cannot be easily compared. In this paper, the average normalized norm of the rows of the error matrix is used to represent the modeling error as follows.

$$e_m = \frac{1}{m}\sum_{i=1}^{m}\sqrt{\frac{\sum_{j=1}^{m}[P_s(i,j)-P_m(i,j)]^2}{\sum_{j=1}^{m}P_s(i,j)^2}} \tag{35}$$

where m is the dimension of the matrices.

First, we demonstrate the accuracy of the proposed finite state Markovian channel model for a single user. Two typical cases are studied to demonstrate the typical accuracy of the analytical model.

DOI: 10.1002/wcm

For $f_m = 8.8\,\text{Hz}$, $\zeta = [10, 5, 0]\,\text{dB}$, $\lambda = 5\,\text{dB}$,

$$\mathbf{P_m} = \begin{bmatrix} 0.9595 & 0.0405 & 0 & 0 \\ 0.0310 & 0.9419 & 0.0271 & 0 \\ 0 & 0.0314 & 0.9627 & 0.0059 \\ 0 & 0 & 0.0500 & 0.9500 \end{bmatrix}$$

$$\mathbf{P_s} = \begin{bmatrix} 0.9621 & 0.0379 & 0 & 0 \\ 0.0294 & 0.9450 & 0.0257 & 0 \\ 0 & 0.0296 & 0.9646 & 0.0058 \\ 0 & 0 & 0.0468 & 0.9532 \end{bmatrix}$$

For $f_m = 8.8\,\text{Hz}$, $\boldsymbol{\zeta} = [10, 7.5, 5, 2.5, 0]\,\text{dB}$, $\lambda = 5\,\text{dB}$,

$$\mathbf{P_m} = \begin{bmatrix} 0.9595 & 0.0405 & 0 & 0 & 0 & 0 \\ 0.0699 & 0.8580 & 0.0721 & 0 & 0 & 0 \\ 0 & 0.0576 & 0.8938 & 0.0487 & 0 & 0 \\ 0 & 0 & 0.0506 & 0.9194 & 0.0300 & 0 \\ 0 & 0 & 0 & 0.0491 & 0.9354 & 0.0155 \\ 0 & 0 & 0 & 0 & 0.0500 & 0.9500 \end{bmatrix}$$

$$\mathbf{P_s} = \begin{bmatrix} 0.9621 & 0.0379 & 0 & 0 & 0 & 0 \\ 0.0665 & 0.8644 & 0.0691 & 0 & 0 & 0 \\ 0 & 0.0547 & 0.8994 & 0.0460 & 0 & 0 \\ 0 & 0 & 0.0481 & 0.9232 & 0.0288 & 0 \\ 0 & 0 & 0 & 0.0463 & 0.9387 & 0.0150 \\ 0 & 0 & 0 & 0 & 0.0468 & 0.9532 \end{bmatrix}$$

Further, the modeling error, e_m, against varying system parameters are given in the following. The summary of the modeling error for a channel with average *SINR* of 5 dB versus varying number of states of the Markov model and fading speed are shown in Figures 3 and 4, respectively. In Figure 3 the x-axis is the normalized maximum Doppler frequency shift that represents the fading speed of the wireless channel. Figure 4 depicts the modeling versus the number of states of Markov process, i.e., the resolution of the model. For varying number of states, we place the threshold values with equal distance between 0 and 10 dB. For example, for $s_n = 7$, the threshold levels are $\zeta = [10, 8, 6, 4, 2, 0]$ dB. It can be seen that the modeling error is fairly negligible (under 2%) for a wide range of system parameters. The error increases with increasing speed of fading process as the Markov property of fading channel decreases. In addition, increasing the number of states results in a larger dimension of the Markov model leading to higher accumulation of modeling error.

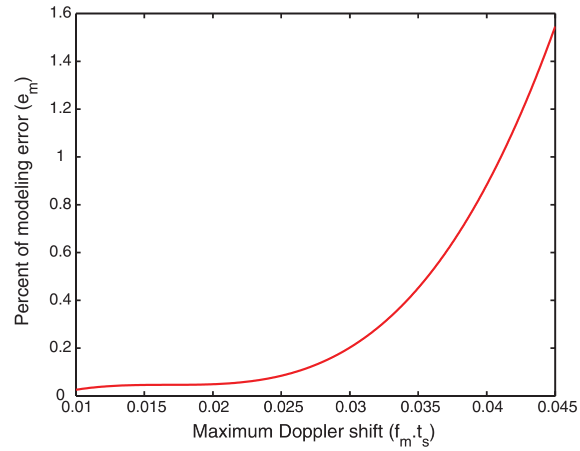

Fig. 3. Modeling error for the channel of a single user versus the speed of fading process (f_m is the maximum Doppler shift and t_s is the time slot length).

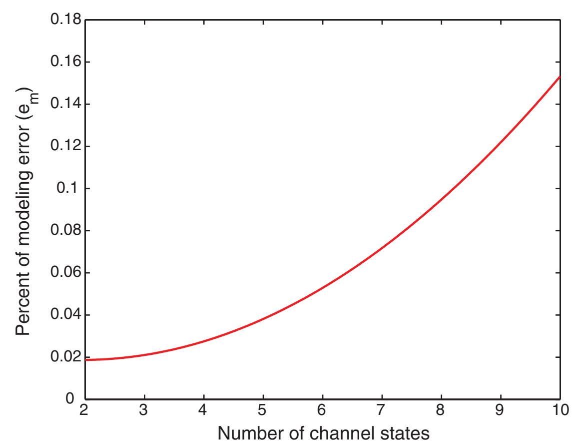

Fig. 4. Modeling error for the channel of a single versus the resolution of the Markov model (number of states).

The simulation and the analytical results for the service model of a single user are given as follows.

For $f_m = 8.8\,\text{Hz}$, $\boldsymbol{\zeta} = [10, 5, 0]\,\text{dB}$, $\lambda = 5\,\text{dB}$, $N = 5$,

$$\boldsymbol{\gamma}_\mathbf{m} = \begin{bmatrix} 0.9099 & 0.0003 & 0.0157 & 0.0708 & 0.0034 \\ 0.8011 & 0.1617 & 0.0372 & 0 & 0 \\ 0.6311 & 0.0005 & 0.3412 & 0.0271 & 0 \\ 0.4018 & 0 & 0.0038 & 0.5880 & 0.0063 \\ 0.0690 & 0 & 0 & 0.0230 & 0.9080 \end{bmatrix}$$

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$$\gamma_{\mathbf{s}} = \begin{bmatrix} 0.9133 & 0.0003 & 0.0147 & 0.0685 & 0.0033 \\ 0.7225 & 0.2291 & 0.0485 & 0 & 0 \\ 0.6017 & 0.0003 & 0.3707 & 0.0273 & 0 \\ 0.3833 & 0 & 0.0039 & 0.6066 & 0.0062 \\ 0.0685 & 0 & 0 & 0.0228 & 0.9088 \end{bmatrix}$$

For $f_m = 8.8\,\text{Hz}$, $\zeta = [10, 7.5, 5, 2.5, 0]\,\text{dB}$, $\lambda = 5\,\text{dB}$, $N = 50$,

$$\gamma_{\mathbf{m}} = \begin{bmatrix} 0.9888 & 0 & 0 & 0 & 0 & 0.0020 & 0.0092 \\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.9239 & 0 & 0 & 0 & 0.0531 & 0.0230 & 0 \\ 0.8545 & 0 & 0 & 0 & 0.0000 & 0.1302 & 0.0153 \\ 0.5073 & 0 & 0 & 0 & 0 & 0.0020 & 0.4907 \end{bmatrix}$$

$$\gamma_{\mathbf{s}} = \begin{bmatrix} 0.9896 & 0 & 0 & 0 & 0 & 0.0019 & 0.0085 \\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.0000 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.8364 & 0 & 0 & 0 & 0 & 0.1493 & 0.0143 \\ 0.4707 & 0 & 0 & 0 & 0 & 0.0019 & 0.5273 \end{bmatrix}$$

The summary of further simulations are shown in Figures 5–7. Figure 5 shows the per-user service model error against the normalized maximum Doppler shift for $s_n = 5$ at $\zeta = [10, 5, 0]\,\text{dB}$ and $N = 10$. Figure 6 is the plot of per-user service model error versus the resolution of the model; the number of users for this figure is 10 and the maximum Doppler shift is 8.8 Hz. The modeling error versus the number of users, for $s_n = 5$ at $\zeta = [10, 5, 0]$ the maximum Doppler shift of 8.8 Hz, is shown in Figure 7.

The simulation results demonstrate a very small deviation from the analytical service model. The increasing error with the increasing speed of fading process, similar to Figure 3, is resulted from the weakening Markov property of the fading process. However, unlike Figure 4, the service model error decreases with the increasing number of states; as the number of states increases there will be more states with zero state probability resulting in reduction of e_m. The increasing number of users has the same impact on the relative number of states as shown in Figure 7.

To demonstrate the application of the results, we use the model to compute the average per-user throughput

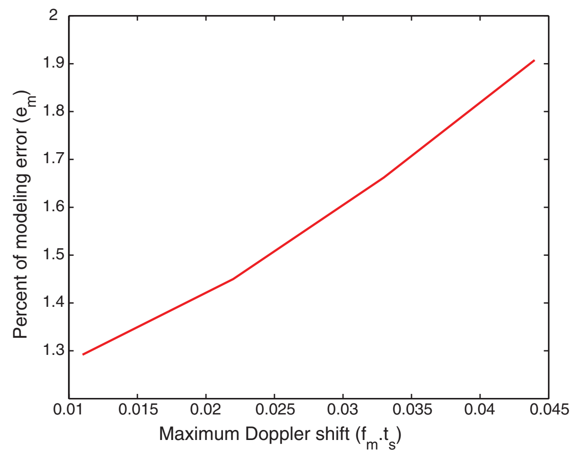

Fig. 5. Service model error versus the speed of fading process (f_m is the maximum Doppler shift and t_s is the time slot length).

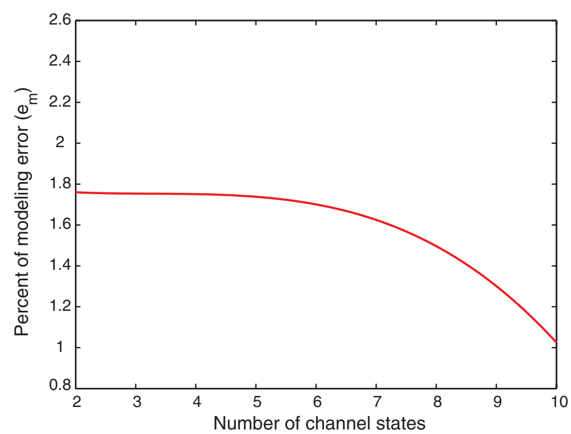

Fig. 6. Service model error versus the resolution of the model (number of states).

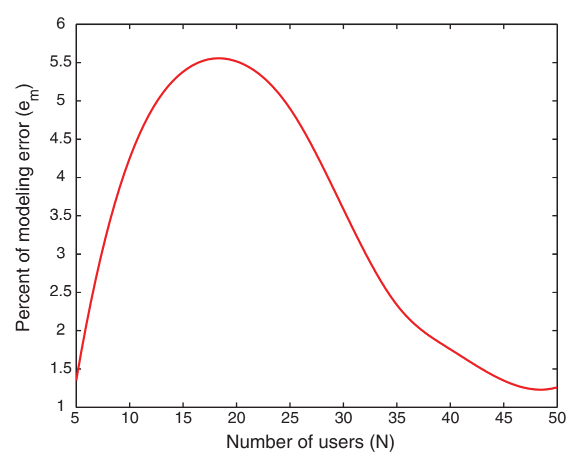

Fig. 7. Service modeling error versus the number of users.

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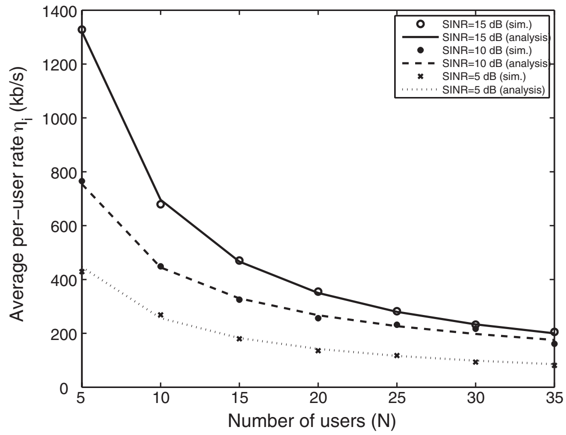

Fig. 8. Average per-user rate versus the number of users.

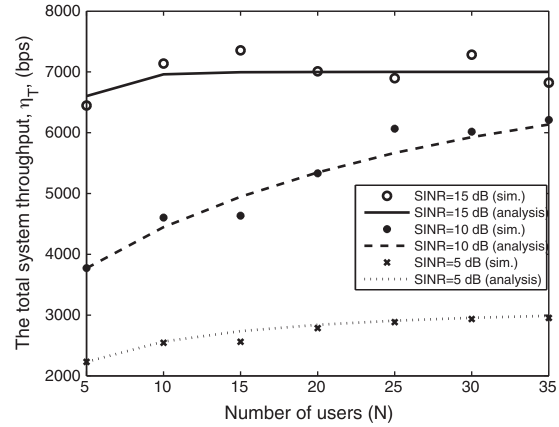

Fig. 10. Total system throughput versus the number of users.

and the total throughput of opportunistic scheduling scheme. Given that the service of a single user is modeled by a Markov model in Figure 12, the average rate of user i is given by

$$\eta_i = \sum_{j=1}^{m} R_{S_j} P_{S_j} \tag{36}$$

where R_{S_j} is the achievable transmission rate in state S_j and P_{S_j} is the steady state probability of being in state S_j. The total system throughput is also given by

$$\eta_T = \sum_{i=1}^{N} \eta_i \tag{37}$$

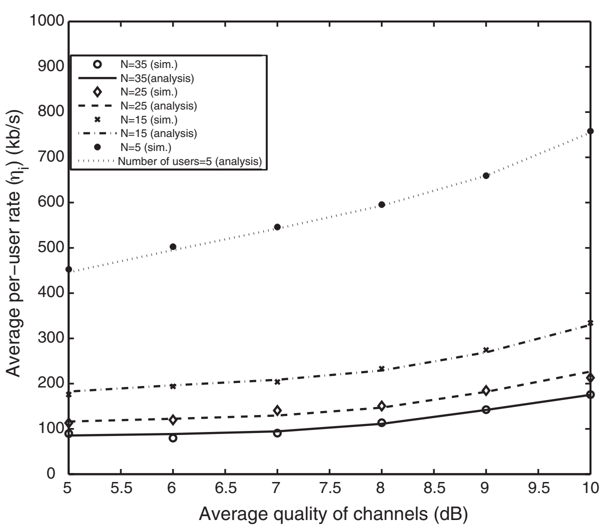

Fig. 9. Average per-user rate versus average quality of channels.

where N is the total number of users. We use the simulation results to verify the accuracy of Equations (36) and (37). Figure 8 shows the average per-user rate of a tagged user versus the total number of users for multiple values of the average quality of wireless channels. Similar results are shown from a different aspect in Figure 9. Variations of the total system throughput versus the number of users is also shown in Figure 10. It can be seen that as the number of users increases the total system throughput increases due to the inherent multiuser diversity gain.

5. Conclusions

In this paper, we considered an opportunistic scheduling of data transmission from a single base station to multiple users. We showed that the dynamics of the received service by a single user can be approximated by an m-state Markov process. Monte Carlo simulation results demonstrated the accuracy of the proposed analytical model. The proposed model considers a saturated scenario, where there is always data for transmission to each in its corresponding buffer in the base station. The future work will focus on the extension of the proposed model to an unsaturated scenario.

Acknowledgments

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Appendix A: Channel Model of a Single User

Fluctuations of the received signal power through a wireless channel due to the destructive and constructive combination of multiple propagations with different path delays and center frequencies is known as fading process. The stochastic model of fading process depends on the propagation model. For a majority of land mobile systems, Rayleigh fading model is a widely accepted one. In this model, the fading process, denoted by $g(t)$, is represented by a complex Gaussian process as follows [17].

$$g(t) = g_I(t) + jg_Q(t) \tag{39}$$

where $g_I(t)$ and $g_Q(t)$ are two zero-mean and white random Gaussian processes. The fading envelope, $|g(t)| = \sqrt{g_I(t)^2 + g_Q(t)^2}$, obviously is a non-white random process. It has been shown in Reference [15] that a first-order Markov process can adequately model the dynamic of Rayleigh fading envelope as illustrated in Figure 11. In this model, the channel is in good state (G) if the normalized fading envelope power, $|g(t)|^2/\Omega$, is above a certain threshold ζ, and in bad state (B), otherwise. For a flat Rayleigh fading channel, the transition probabilities are given by Reference [15]

$$v = \frac{Q(\theta, \rho\theta) - Q(\rho\theta, \theta)}{e^{\zeta} - 1}$$
$$u = \frac{1 - e^{-\zeta}}{e^{-\zeta}} v \tag{40}$$

where $Q(\cdot, \cdot)$ is the Marcum Q function,

$$\theta = \sqrt{\frac{2\zeta}{1 - \rho^2}}$$

and

$$\rho = J_0(2\pi f_m T)$$

$J_0(\cdot)$ is the zero-order Bessel function of the first kind, f_m is the maximum Doppler frequency shift, and T is the time span between two consecutive samples of the fading envelope. In our case, T is equal to the length of a time slot.

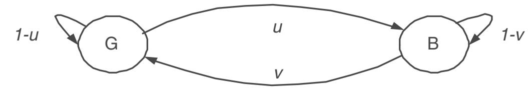

Fig. 11. Two-state Markov model for fading channels.

We extend the simple two-state model, given by Equation (40), to obtain an m-state Markov model with arbitrary number of states, as illustrated in Figure 12. Although m-state models for fading channels have been proposed [16], our approach is novel and simple in the sense that it extends the very well know two-state model. The curve on the left depicts a sample normalized envelope power at the receiver. The vertical axis is divided into several sections. When the signal power is below ζ_i and above ζ_{i-1} the channel is in state i, as indicated by the Markov model in the right. Considering Equation (40) with the threshold level i yields a pair of transition probabilities as

$$v_i = \frac{Q(\theta, \rho\theta) - Q(\rho\theta, \theta)}{e^{\zeta_i} - 1}$$
$$u_i = \frac{1 - e^{-\zeta_i}}{e^{-\zeta_i}} v_i \tag{41}$$

and

$$\xi_i = 1 - e^{-\zeta_i} \tag{42}$$

which represents the probability that the received normalized signal power, $|g(t)|^2/\Omega$, is below ζ_i. The

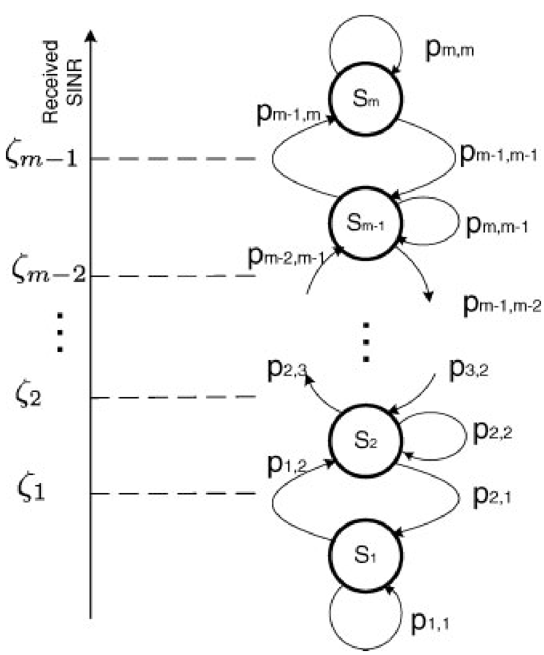

Fig. 12. Finite-state Markov model for fading channels.

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number of states, m, depends on the resolution of the available information.

We use the primitives v_i, u_i, and ξ_i to compute transition probabilities of the m-state Markov model in Figure 12. Let $s_i(t)$ represent the event that the channel is in state i at time slot t. According to the definition of transition probability in a Markov process,

$$\begin{aligned} p_{i,i+1} &= \Pr\{s_{i+1}(t)|s_i(t-1)\} \\ &= \frac{\Pr\{s_{i+1}(t) \cap s_i(t-1)\}}{\Pr\{s_i(t-1)\}} \end{aligned} \tag{43}$$

where $\cup$ and $\cap$ denote union and intersection of events, respectively. Hence, we need to find $\Pr\{s_{i+1}(t) \cap s_i(t-1)\}$ and $\Pr\{s_i(t-1)\}$ in order to compute $p_{i,i+1}$. From Equations (41) and (42), we can directly conclude

$$\Pr\{s_i(t-1)\} = \xi_i - \xi_{i-1} \tag{44}$$

To obtain $\Pr\{s_{i+1}(t) \cap s_i(t-1)\}$, first, we prove that $\Pr\{s_{i+1}(t) \cap s_i(t-1)\} = \Pr\{|g(t)|^2/\Omega \geq \zeta_i \cap |g(t-1)|^2/\Omega \leq \zeta_i\}$. We expand the term on the right hand side as

$$\begin{aligned} &\Pr\left\{|g(t)|^2/\Omega \geq \zeta_i \cap |g(t-1)|^2/\Omega \leq \zeta_i\right\} = \\ &\Pr\Big\{\left[s_m(t) \cup \cdots \cup s_{i+1}(t)\right] \cap \\ &\left[s_i(t-1) \cup \cdots \cup s_1(t-1)\right]\Big\} = \\ &\Pr\Big\{\left[[s_m(t) \cup \cdots \cup s_{i+1}(t)] \cap s_i(t-1)\right] \cup \\ &\vdots \\ &\left[[s_m(t) \cup \cdots \cup s_{i+1}(t)] \cap s_1(t-1)\right]\Big\} = \\ &\Pr\Big\{\Big[\big(s_m(t) \cap s_i(t-1)\big) \cup \cdots \cup \big(s_{i+1}(t) \cap s_i(t-1)\big)\Big] \cup \\ &\vdots \\ &\Big[\big(s_m(t) \cap s_1(t-1)\big) \cup \cdots \cup \big(s_{i+1}(t) \cap s_1(t-1)\big)\Big]\Big\} \end{aligned} \tag{45}$$

Recall from Figure 12 that only transitions among neighbor states are possible. Thus, any $\big(s_k(t) \cap s_l(t-1)\big)$ for $|k-l| > 1$ is an empty set. Hence, all terms in Equation (45), except $\big(s_{i+1}(t) \cap s_i(t-1)\big)$, can be eliminated. In other words, $\Pr\{s_{i+1}(t) \cap s_i(t-1)\} = \Pr\{|g(t)|^2/\Omega \geq \zeta_i \cap |g(t-1)|^2/\Omega \leq \zeta_i\}$. On the other hand, from the definition of transition probabilities for a two-state Markov model in Equation (41),

$$v_i = \frac{\Pr\left\{|g(t)|^2/\Omega \geq \zeta_i \cap |g(t-1)|^2/\Omega \leq \zeta_i\right\}}{\Pr\left\{s_i(t-1) \cup \cdots \cup s_i(t-1)\right\}} \tag{46}$$

Knowing that $\Pr\{s_{i+1}(t) \cap s_i(t-1)\} = \Pr\{|g(t)|^2/\Omega \geq \zeta_i \cap |g(t-1)|^2/\Omega \leq \zeta_i\}$ and $\Pr\left\{s_i(t-1) \cup \cdots \cup s_i(t-1)\right\} = \xi_i$, Equation (46) can be simplified to

$$v_i = \frac{\Pr\{s_{i+1}(t) \cap s_i(t-1)\}}{\xi_i} \tag{47}$$

Finally, combining Equations (43), (44), and (47) yields

$$p_{i,i+1} = \frac{\xi_i}{\xi_i - \xi_{i-1}} v_i \tag{48}$$

Similarly, we can show that

$$p_{i+1,i} = \frac{1-\xi_i}{\xi_{i+1} - \xi_i} u_i \tag{49}$$

Referring to Figure 12,

$$p_{i,i} = 1 - p_{i,i+1} - p_{i,i-1} \tag{50}$$

The proposed model is verified by simulation results in Section 4.

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Authors' Biographies

Mehrdad Dianati is a RCUK Academic Fellow in Mobile Communication Research Group of CCSR. He completed his undergraduate and master degrees with distinction in Sharif University (Iran) and K.N.T University (Iran). He received his Ph.D. degree in Electrical and Computer Engineering from the University of Waterloo, Canada, in June 2006, in radio resource management. From June 2006 to June 2007 he has been a post-doc researcher at École Nationale Supérieure des Télécommunications (ENST), France. He has also several years of industrial experience as team leader and project manager. He is the member of the Editorial Board for the International Journal of Ultra Wide Band Communication Systems.

Rahim Tafazolli is a Professor of Mobile/Personal communications and Head of Mobile Communications Research at Centre for Communication Systems Research (CCSR), the University of Surrey, UK. He has been active in research for over 20 years and has authored and co-authored more than 300 papers in refereed international journals and conferences. Professor Tafazolli is a consultant to many mobile companies, has lectured, chaired and being invited as keynote speaker to a number of IET and IEEE workshops and conferences. He is the Founder and past Chairman of IET International Conference on 3rd Generation Mobile Communications. He is the Chairman of EU Expert Group of E-mobility Technology Platform.

Xuemin (Sherman) Shen (IEEE M'97-SM'02-F'09) received the B.Sc.(1982) degree from Dalian Maritime University (China) and the M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey (USA), all in electrical engineering. He is a Professor and University Research Chair, Department of Electrical and Computer Engineering, University of Waterloo, Canada. Dr. Shen's research focuses on mobility and resource management in interconnected wireless/wired networks, UWB wireless communications networks, wireless network security, wireless body area networks and vehicular ad hoc and sensor networks. He is a co-author of three books, and has published more than 400 papers and book chapters in wireless communications and networks, control and filtering. Dr. Shen served as the Tutorial Chair for IEEE ICC'08, the Technical Program Committee Chair for IEEE Globecom'07, the General Co-Chair for Chinacom'07 and QShine'06, the Founding Chair for IEEE Communications Society Technical Committee on P2P Communications and Networking. He also serves as a Founding Area Editor for IEEE Transactions on Wireless Communications; Editor-in-Chief for Peer-to-Peer Networking and Application; Associate Editor for IEEE Transactions on Vehicular Technology; KICS/IEEE Journal of Communications and Networks, Computer Networks; ACM/Wireless Networks; and Wireless Communications and Mobile Computing (Wiley), etc. He has also served as Guest Editor for IEEE JSAC, IEEE Wireless Communications, IEEE Communications Magazine, and ACM Mobile Networks and Applications, etc. Dr. Shen received the Excellent Graduate Supervision Award in 2006, and the Outstanding Performance Award in 2004 and 2008 from the University of Waterloo, the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University

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of Waterloo. Dr. Shen is a registered Professional Engineer of Ontario, Canada, and a Distinguished Lecturer of IEEE Communications Society.

Kshirasagar Naik received his BS and M. Tech degrees from Sambalpur Unversity, India, and the Indian Institute of Technology, Kharagpur, respectively. He received an M. Math degree in computer science from the University of Waterloo and a Ph.D. degree in electrical and computer engineering from Concordia University, Montreal. He worked as a faculty member at the University of Aizu in Japan, and Carleton University in Ottawa. At present he is an associate professor in the Department of Electrical and Computer Engineering, at the University of Waterloo. He was a visiting associate professor at the Research Institute of Electrical Communications at Tohoku University, Sandai, Japan, in 2003. He served as a program co-chair of the 5th International Conference on Information Technology held in Bhubaneswar, India, in December 2002. He was a co-guest editor of two special issues of IEEE Journal on Selected Areas in Communications published in June 2005 and January 2007. Now he is an associate editor for the Journal of Peer-to-Peer Networking and Applications and the International Journal of Parallel, Emergent and Distributed Systems. His research interests include testing of communication protocols, wireless communication, and resource allocation in cellular networks, sensor networks, ad hoc networks, mobile computing, peer-to-peer communication, and intelligent transportation systems.

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