Applying Opportunistic Spectrum Access in Mobile Cellular Networks

Ádám Horváth

***Abstract*—Nowadays, mobile service providers (SPs) have the exclusive access of certain spectrum for the mobile telecommunication services. This approach may lead to the inefficient use of the spectrum, which can be alleviated by opportunistic spectrum access.**

In this paper, we propose a cooperation scheme for mobile SPs, in which the SPs can use each other's unutilized frequency bands, when their own speech channels are occupied. Our simulation results show that significant gain in the blocking ratio and in the utilization can be achieved with the proposed cooperation scheme. Moreover, we calculate the average profit rate, and show that our scheme is beneficial for both cooperating party.

***Index Terms*—opportunistic spectrum access, mobile cellular networks, spectrum sharing policy;**

I. Introduction

PRESENTLY, mobile network operators have exclusive right for the use of given frequency bands, which were assigned to them by the governments on spectrum auctions. Each mobile operator is restricted to its dedicated channels when allocating an incoming call, and the requests for speech channels will be rejected if the dedicated speech channels are occupied. However, the exclusive frequency usage may lead to an inefficient use of the spectrum [1], [2], [3].

To handle the inefficiency, several researchers proposed spectrum sharing techniques such as spectrum renting or opportunistic spectrum access (OSA). Bernal-Mor et al. analyzed three different models for renting individual speech channels [4]. Many papers dealt with the technical aspects of OSA [1], [2], [5], [6] and some proposed spectrum auctions for achieving the dynamic spectrum access [7], [8]. Nevertheless, only few made an attempt to really model the operation of a network assuming cooperation between service providers [9], [10], [3].

Moreover, the authors in [9] and [10] tried to model the spectrum renting. However, they ignored that the current specification of mobile cellular networks does not allow the renting of a single speech channel [3]. Therefore, these models are not realistic in the current technical environment. In [3], the authors proposed a Markovian model for modeling spectrum renting and investigated some renting policies. They showed that their model using exponentially distributed holding times is a good approximation of the operation of a mobile cellular network, where the holding times follow the log-normal distribution [11]. In their model [3], only one service provider is present and the environment is modeled as a stochastic process, which makes their model mathematically tractable.

Manuscript submitted March 28, 2013, revised May 14, 2013.

Á. Horváth is with the University of West Hungary, Institute of Informatics and Economics, Sopron, H-9400, Hungary (email: horvath@inf.nyme.hu)

In this paper, we re-positioned the model of [3] as follows. First, we assume that two competing SPs are present, by which we can investigate the effects of the cooperation at both SPs at the same time. Second, we propose a new cooperation scheme using a spectrum sharing policy for mobile SPs, in which the SPs minimize the renting time by the opportunistic use of external frequency bands. Our simulation results show that the high level of cooperation (OSA) results a significant gain for the SPs. Namely, the blocking ratio decreases extremely and the utilization is higher. We also show that achieving a significant gain in the blocking ratio does not need the frequent use of external frequency bands. Moreover, we calculate the average profit rate (APR) to demonstrate that our cooperation scheme is financially advantageous for both SPs. Since this work focuses on the operation of the model, we do not deal with the technical details like signaling between the SPs.

The rest of the paper is organized as follows. In Section II, we describe a cooperation policy between the SPs in detail. In Section III, we describe the proposed operational practice, while we present some simulation results in Section IV. We conclude the paper in Section V.

II. The Proposed Spectrum Sharing Policy

At present, there are competitive service providers delivering mobile communication service in each country. The frequency bands which they use to serve their clients are owned by the local government. The mobile communication companies compete for the license of the frequency usage on spectrum auctions. On each frequency band, the SPs can allocate 8 full-rate or 16 half-rate speech channels, on which they can allocate the incoming calls.

Each service provider divides its network into disjoint cells and tries to cover the whole area of the given country. In most cases, the mobile cells of the different providers cover each other, so more than one SPs are available on a given geographical place. Presently, if all speech channels of one service provider are occupied new incoming calls are blocked while there may be available channels at another operator.

However, if two arbitrary SPs (SP_A and SP_B) would cooperate according to the scheme presented below, more clients could be served. To facilitate it, we propose the following cooperation scheme. The SPs continuously monitor each other's spectrum to obtain which frequency bands are unused (a frequency band is unused, if there is no allocated call on it). If all speech channels of SP_A are occupied, SP_A may opportunistically allocate the new incoming calls on SP_B's unused frequency band f. Due to the current technical constraints, the SPs cannot share a frequency band for simultaneous use [3]. Therefore, while SP_A is using f, SP_B cannot use it, even if only one speech channel is occupied on f.

In our model, a SP allows to use its unused frequency bands if the other SP needs it (of course, a renting fee must be paid for the frequency renting). Moreover, SP_B uses as few frequency bands as possible to increase the probability of successful frequency renting for SP_A. To achieve this, SP_B consolidates its network every time when an ongoing call is terminated, i.e. re-allocates the rest of ongoing calls. If SP_A is already using at least one frequency band of SP_B, the consolidation aims to vacate the rented frequency bands first in order to minimize the renting fee. The consolidation process ensures that a SP uses always the ”required number” of frequency bands simultaneously, i.e., at most one used frequency band exists in a given moment on which there is at least one free channel. Formally, if the number of channels per frequency band is c, the number of ongoing calls is n, the number of used frequency bands can be computed as $\lceil \frac{n}{c} \rceil$.

If SP_B's speech channels are also occupied, and needs the channels which are currently used by SP_A, SP_A must vacate the rented frequency band and terminate the ongoing calls allocated on that frequency band. These ongoing calls suffer the forced termination, since the consolidation rule ensures that all speech channels in SP_A's network are occupied. Therefore, there are two ways of blocking in OSA: the normal blocking (NB), when the home network is saturated and there is no other available frequency band; and the forced blocking (FB), when an ongoing call is broken due to frequency withdrawal. In case of forced blocking, a user has got the service for a given time, however, it is annoying for him to suffer the break of the connection.

From SP_B's point of view, the frequency renting results financial benefits for him, since the renting fee must be paid for it. When SP_B needs the rented frequency band, it can be withdrawn without any disadvantageous consequence. The only disadvantage for SP_B is that the frequency renting helps the concurrent provider, too. From SP_A's viewpoint, the frequency renting is an additional option to avoid the blocking of the incoming calls. Without renting, the incoming calls would be blocked, however, the forced termination problem still holds. The break of the connection is annoying for the users, but it is still possible that most users are served without forced termination and without knowing that their call was allocated on an external frequency band.

In our investigations, we assume that two SPs (SP_A and SP_B) are present, and we compare the cases when both SPs use OSA or they do not cooperate.

III. System Model

In this section, we describe our system model, in which SPs use OSA and follow the policy that was detailed in Section II.

A. Notations

Henceforth, we use some notations that we collected in Table I.

TABLE I
NOTATIONS

Notation	Description
N_x	The number of speech channels of $SP_x, x \in A, B$
n_x	The number of frequency bands of $SP_x, x \in A, B$
c	The number of channels per frequency band ($N_x = n_x \cdot c$) $x \in A, B$
b_x	The number of occupied channels at $SP_x, x \in A, B$ (including the occupied rented channels)
f_x	The number of own frequency bands used at $SP_x, x \in A, B$
g_x	The number of rented frequency bands by $SP_x, x \in A, B$

B. The operation of the model

Using the variables of Table I, we can unambiguously determine whether an incoming call at a given SP can be served or will be blocked. Moreover, we can determine if an incoming call at a given SP causes forced blocking at the other SP.

In our model, the system is controlled by two main events: a *call arrival* (CA), when a SP should serve an incoming call, and a *channel release* (CR), when a call is terminated by the user. The following flowcharts present how our model operates when these events occur (Fig. 1 and Fig. 2).

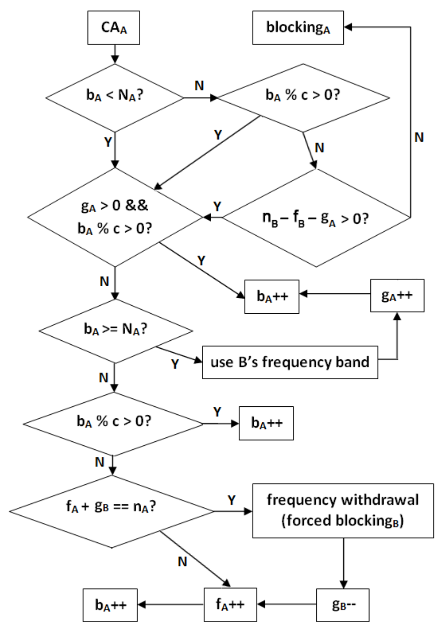

Fig. 1. System operation when a CA event occurs at SP_A

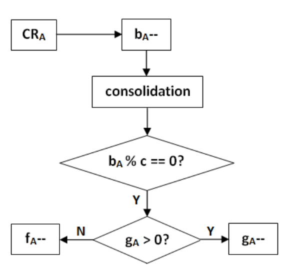

Fig. 2. System operation when a CR event occurs at SP_A

Fig. 1 represents the CA event. If an incoming call arrives e.g. at SP_A, there are three possible ways of serving it. First, if SP_A has got more own channels than the number of calls under service (even if SP_A must withdraw a channel from SP_B). Then, if the home network is saturated, but SP_A is currently using a frequency of SP_B and there is at least one free channel on that frequency band (namely, $b_A \ \% \ c > 0$). Finally, if the previous two conditions are not met, SP_A can use another frequency band of SP_B, if at least one of them is free. If none of the above mentioned conditions are fulfilled, the incoming call will be blocked. Note that without OSA, SP_A must have blocked the incoming call after the $first$ condition is unsatisfied.

If SP_A can serve the incoming call, a channel must be allocated for it, so it must be checked which condition of the above mentioned ones is met. First, if SP_A already uses at least one frequency band of SP_B ($g_A > 0$), and there is no need to use another frequency band of SP_B ($b_A \ \% \ c > 0$), SP_A serves the call on a frequency band of SP_B that SP_A has already been using (b_A++). If the first condition is not satisfied, SP_A checks whether the number of users under service is greater or equal to the number of its own channels ($b_A \geq N_A$). If so, SP_A must use another free frequency band of SP_B and serve the incoming call on that frequency band. If neither of the first two conditions are satisfied, SP_A will serve the incoming call on its own frequency band, on which there is no ongoing call of its own customers. However, SP_A must check if it must withdraw an own frequency band from SP_B to serve the incoming call ($f_A + g_B \stackrel{?}{=} N_A$). If so, SP_A will withdraw its own frequency band from SP_B (forced blocking at SP_B), else SP_A will use its own free frequency band.

Fig. 2 represents the CR event. If an ongoing call is terminated by the user e.g. in SP_A's system, SP_A's network must be consolidated to ensure that SP_A always uses only the minimum number of frequency bands on which its customers can be served. If one frequency band will be free after the consolidation ($b_A \ \% \ c = 0$), SP_A must check if that frequency band is SP_B's band ($g_A > 0$). If so, SP_A stops using SP_B's frequency band.

IV. Simulation Results

In this section, we present some numerical results obtained with the use of SimPack [12] that was proved as an effective event-driven simulation tool in many performance evaluation studies [3], [13], [14], [15].

A. Definitions

In the following scenarios, we present our results as a function of the normalized load $load_{norm}$, which can be computed as follows.

$$load_{norm} = \frac{\lambda_A}{N_A}\frac{1}{\mu_A}, \tag{1}$$

where $1/\lambda_A$ is the average time interval between the arrivals at SP_A, $1/\mu_A$ is the average holding time, and N_A is the number of SP_A's speech channels.

If we really want to demonstrate the financial benefits of our cooperation scheme, we must explicitly present financial parameters like APR, which can be computed as follows.

$$APR = \alpha \times \bar{S} - \beta \times (\bar{R} - \bar{L}), \tag{2}$$

where α and β are cost coefficients measured in cost units per time unit for the calls and the renting, respectively [3]; $\bar{S}$ is the total duration of the calls, $\bar{R}$ is the total duration of the renting, and $\bar{L}$ is the duration when the other SP was using the current SP's frequency bands. When we determine the renting fee, we must take into account that a SP will have c additional channels when renting a frequency band. In our model, we assume that at least one ongoing call is using the rented frequency band. On the other hand, the rented channel is usually not fully utilized, since there are expectedly less than 8 ongoing calls on it. Therefore, the renting fee should be less than the total income from a fully utilized frequency band (i.e. $\alpha \times c$). So, we define a discount factor and calculate the renting fee as follows.

$$\beta = \alpha \times \frac{c}{d}, \tag{3}$$

where $c > d \geq 1$ is the discount factor (note that $d = 1$ means no discount).

B. Simulation settings

In the case study, the channel holding times are log-normally distributed with the mean of 4.0 seconds and the standard deviation of 1.17 seconds. These values are taken from [11] and derived from observing real data traffic. This means that the expected channel holding time is 108.25 seconds in our model.

Moreover, Pattavina and Parini showed that the interarrival time distribution also follows the log-normal distribution [16]. Based on the parameter settings of [16], the mean interarrival time runs from 7.83 to 7.21 seconds to achieve a blocking ratio of 1-2% when the SPs did not cooperate. In the simulations, each SP has got 3 frequency bands in the investigated mobile cell, which means 24 full-rate speech channels for each SP if they do not cooperate.

Besides, we applied a policy, according to which the SPs do not pay any renting fee to each other in the cases when the given frequency band was withdrawn. This rule can be a compensation for breaking the ongoing connections (of course, $\bar{R}$ will be not increased with the time interval of the broken renting when computing the APR).

We investigated some properties at a given SP assuming the use of OSA, then without cooperation, as well. These properties are the blocking ratio; the average number of occupied channels; the ratio of external frequency bands used ($g_A/(f_A + g_A)$ or $g_B/(f_B + g_B)$); and the APR.

The simulation results are obtained with the confidence level of 99.9% and the relative precision (i.e. the ratio of the half-width of the confidence interval and the mean of collected observations) of 0.8%.

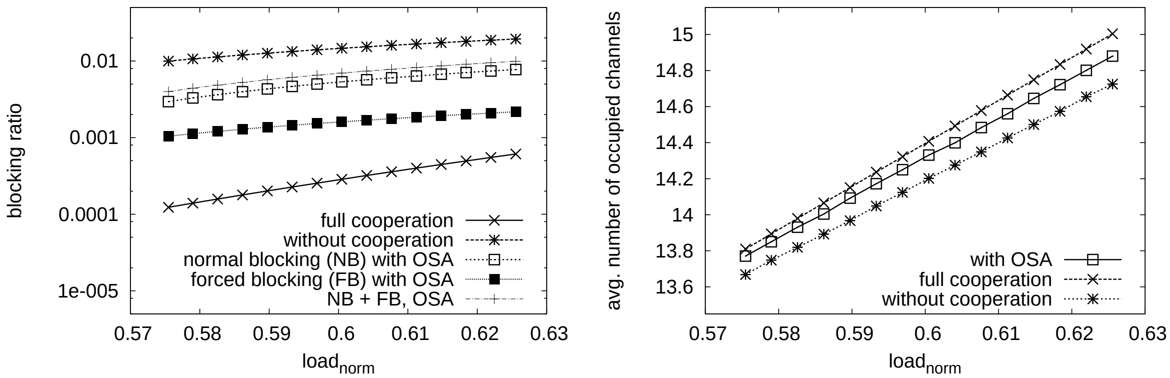

Fig. 3. Scenario 1 – the ratio and the average number of occupied channels

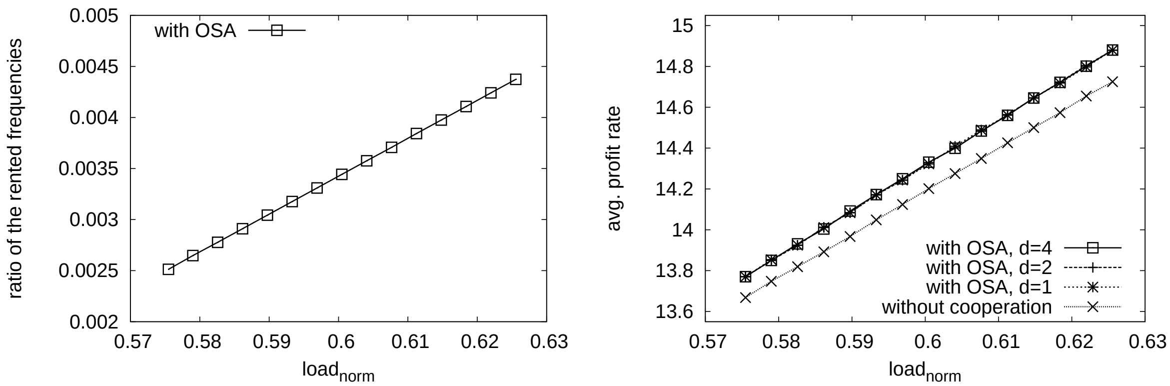

Fig. 4. Scenario 1 – the ratio of the rented frequency bands and the average profit rate

C. Scenario 1

In the first scenario, the normalized load is increasing at both SPs. Fig. 3 and Fig. 4 show the simulation results.

The left graph in Fig. 3 represents the blocking ratio of SP_A as a function of the normalized load. As Fig. 3 illustrates, the blocking ratio by using OSA is significantly lower than if the SPs would not cooperate (note that we use logarithmic scale when depicting the blocking ratio). In the left graph of Fig. 3, we also represent the blocking ratio assuming a full cooperation, which is equivalent with the fusion of the two SPs ensuring double capacity and double customer number. We also would get the full cooperation case if the SPs could rent single speech channels from each other. This graph also shows the forced blocking when using OSA, which is significantly lower than the normal blocking. Moreover, we represented the sum of the normal blocking and the forced blocking when we used OSA.

In the right graph of Fig. 3, the average number of occupied channels is shown. Using OSA, the average number of occupied channels is around 14.9 when the load is 0.625, while this value is only 14.7 without cooperation. Therefore, beside the decrease of the blocking ratio, the utilization increases using OSA.

The left graph of Fig. 4 depicts the ratio of external frequency bands used to the total number of frequency bands used by SP_A when OSA was applied. Even when the load is 0.625, this value is below 0.45%, which means that SP_A could serve its customers on its own frequency bands in most cases. When not, SP_A had the possibility of frequency renting, which resulted a notable gain in the blocking ratio, as we can see in the left graph of Fig. 3.

In the left graph of 4, the APR value is illustrated. When the SPs cooperate according to our scheme, a significant gain can be achieved in the APR. We investigated the APR with different values of d, however, the results show that there was no impact of d on the APR in this case. The explanation of this is that when the traffic is equal and equally changes at both SPs, the probability that they will use each other's channel is also equal. Henceforth, we will demonstrate the impact of d in Section IV-D.

D. Scenario 2

In the second scenario, we investigated the APR when the load of SP_A is increasing as in Scenario 1, while SP_B's load is constant with around 1% expected blocking ratio.

The graphs of 5 represent the APR values of SP_A (left side) and SP_B (right side). As the traffic increases, the APR of SP_A increases, as well. Of course, the higher the discount factor is, the higher APR can be realized for the renter. Even if the discount factor is one, the APR is higher than without cooperation, which can be explained as follows. First, SP_A also has income from the renting fee, since SP_B also

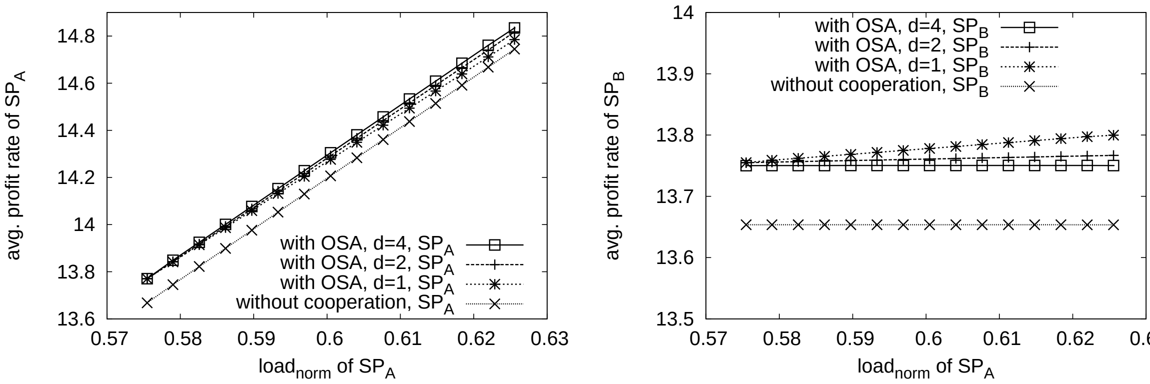

Fig. 5. Scenario 2 – the average profit rate of SP_A and SP_B

uses SP_A's frequency bands when necessary. Second, the compensation rule allows SP_A not to pay any renting fee if the given frequency band was withdrawn. On the other hand, SP_B can increase its profit only due to the increase of SP_A's traffic, when the SPs cooperate. Even if SP_B offers a discount of $d = 2$ or $d = 4$, the gain is significant.

V. Conclusions

In this paper, we presented a realistic model for investigating the effects of opportunistic spectrum access in mobile cellular networks. In our simulations, two competing SPs cooperate and allow each other to opportunistically use their spectrum. The results showed that both SPs have significant gain in the main system parameters like the blocking ratio and the utilization, while the forced blocking was marginal in each investigated case. Besides, our investigations showed that both SPs can increase their average profit rate when they cooperate: one from the renting fee, the other due to the increased capacity. Since our model involves a new signaling method, developing the signaling algorithm would be an interesting future work. Moreover, a work on a mathematical model is under progress.

Acknowledgement

The author thanks his supervisors: Prof. Tien Van Do, Department of Telecommunications, Budapest University of Technology and Economics and Prof. László Jereb, University of West Hungary, for the professional support and guidance during the preparation of this paper.

Ádám Horváth received the M.Sc. degree in Computer Science from the Budapest University of Technology and Economics (BME) in 2007. After his M.Sc. he joined the Institute of Informatics and Economics at the University of West Hungary as a Ph.D. student under the supervision of Prof. Károly Farkas. His research interests cover security of wireless networks and mathematical modeling, mainly focused on Markovian processes.

References

[1] J. M. Peha, "Sharing spectrum through spectrum policy reform and congitive radio," in *in Proceedings of the IEEE*, vol. 97, pp. 708–719, 2009.

[2] B. Jabbari, R. Pickholtz, and M. Norton, "Dynamic Spectrum Access and Management (Dynamic Spectrum Management)," *IEEE Wireless Communications*, vol. 17, no. 4, pp. 6–15, 2010.

[3] T. V. Do, N. H. Do, and R. Chakka, "A new queueing model for spectrum renting in mobile cellular networks," *Computer Communications*, vol. 35, no. 10, pp. 1165–1171, 2012.

[4] E. Bernal-Mor, V. Pla, and J. Martinez-Bauset, "Analysis of different channel sharing strategies in cognitive radio networks," in *Proceedings of the Third international conference on Multiple access communications*, MACOM'10, (Berlin, Heidelberg), pp. 70–73, Springer-Verlag, 2010.

[5] A. Ghasemi and E. Sousa, "Optimization of spectrum sensing for opportunistic spectrum access in cognitive radio networks," in *in Proceedings of the IEEE Consumer Communications and Networking Conference, Las Vegas, Nevada, USA*, pp. 1022–1026, 2007.

[6] S. Öner and F. Jondral, "On the Extraction of the Channel Allocation Information in Spectrum Pooling Systems," *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 3, pp. 558–565, 2007.

[7] S. Gandhi, C. Buragohain, L. Cao, H. Zheng, and S. Suri, "Towards Real-Time Dynamic Spectrum Auctions," *Computer Networks*, vol. 52, no. 4, pp. 879–897, 2008.

[8] E. M. Noam, "Taking the Next Step Beyond Spectrum Auctions: Open Spectrum Access," *Telecommunications Policy*, vol. 21, pp. 461–475, 1997.

[9] S.-S. Tzeng and C.-W. Huang, "Threshold based call admission control for qos provisioning in cellular wireless networks with spectrum renting," in *Novel Algorithms and Techniques in Telecommunications and Networking* (T. Sobh, K. Elleithy, and A. Mahmood, eds.), pp. 17–22, Springer Netherlands, 2010.

[10] S.-S. Tzeng, "Call Admission Control Policies in Cellular Wireless Networks with Spectrum Renting," *Computer Communications*, vol. 32, pp. 1905–1913, 2009.

[11] C. Jedrzycki and V. C. M. Leung, "Probability Distribution of Channel Holding Time in Cellular Telephony Systems," in *in Proceedings of the IEEE VTC'96, Atlanta, Georgia, USA*, pp. 247–251, 1996.

[12] P. Fishwick, "SimPack: Getting Started With Simulation Programming In C and C++," in *in Proceedings of the Winter Simulation Conference*, pp. 154–162, 2002.

[13] T. V. Do, "An Efficient Solution to a Retrial Queue for the Performability Evaluation of DHCP," *Computers & OR*, vol. 37, no. 7, pp. 1191–1198, 2010.

[14] T. V. Do, "A new computational algorithm for retrial queues to cellular mobile systems with guard channels," *Computers & Industrial Engineering*, vol. 59, no. 4, pp. 865 – 872, 2010.

[15] T. V. Do, "Solution for a retrial queueing problem in cellular networks with the fractional guard channel policy," *Mathematical and Computer Modelling*, vol. 53, no. 11–12, pp. 2058–2065, 2011.

[16] A. Pattavina and A. Parini, "Modelling voice call inter-arrival and holding time distributions in mobile networks," *Performan. Challenges Efficient Next Generat. Networks, Proc. 19th Int. Teletraf. Congr*, pp. 729–738, 2005.