Performance Evaluation of Priority-Based CDMA Systems in the Presence of Multirate Poisson Traffic

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***Abstract*—Next-generation cellular networks are expected to support a wide range of communication technologies and user devices. Under such conditions, proper modelling of user traffic and system performance evaluation is of major importance. In this paper, we employ mathematical modelling techniques to analyse the performance of a single CDMA cell under the presence of user-generated multirate Poisson traffic. We also explicitly consider different traffic priority classes in the system. The proposed model enables us to determine the resource occupancy of the cellular system at different system states and to accurately calculate call blocking probabilities for different services. In particular, we describe the CDMA system as a continuous-time Markov chain and derive formulas for system state probabilities. We also perform thorough simulation experiments to validate the accuracy of the derived equations.**

I. INTRODUCTION

Due to heterogeneous nature of next-generation cellular systems, proper evaluation of radio resource management techniques is of major importance [1]. Analytical modelling and evaluation of such systems is a challenging task, especially under the presence of user-generated multirate traffic. In this work, we focus on a well-known family of Code Division Multiple Access (CDMA) techniques [2]. CDMA-based schemes have been successfully used in previous and current generation cellular networks. They offer efficient spectrum utilization, improved signal quality and security, just to name a few. For these reasons, they are also expected to play a significant role in the under development, next generation cellular technologies [3], [4], [5].

As far as the traditional cellular model is concerned, the geographical area is divided into a number of cells, with each cell being controlled by a Base Station (BS). Communication between BSs is performed via the core network, using either wired or wireless backhaul [6]. On the other hand, in future-generation networks the introduction of intelligent BSs would enable direct communication among them even for user traffic delivery [7]. Furthermore, recent advances in Software Defined Radio Access Network (SD-RAN) [8] enable cooperation among neighbouring BSs for user mobility support, without relying on the mobile core network [9].

Traditionally, Mobile Users (MUs), communicate with each other via the corresponding BSs. However, recent enhancements in Device-to-Device (D2D) techniques, can greatly reduce the role of BSs both for signalling and user traffic [10]. For practical reasons, CDMA codes are non-orthogonal. Due to this reason, each new MU in a cell causes interference to other MUs, both of the same and of neighbouring cells. Hence, to preserve the Quality-of-Service (QoS) of existing MUs at an acceptable level, Call Admission Control (CAC) is usually applied for incoming calls [11]. As a consequence, some of the calls may be blocked or accepted at a lower transmission rate.

In this paper, we develop a mathematical model for a CDMA cell, which uses a continuous-time Markov chain (CTMC) to describe the process of call arrivals and departures. We consider Poisson arriving calls, which however, are distinguished into different priority classes. That is, when the cell is congested, the low priority calls may be blocked according to a set of predefined thresholds. Our analysis is based on the classical Kaufman-Roberts (K-R) recursion [12], [13]. These solutions, which have been developed for wired connection-oriented networks, are extended in our work to incorporate the peculiarities of priority-based cellular systems.

This paper is structured as follows. In Section II, we describe our considered model of a CDMA cell. In Section III, we analyse the model using a CTMC. Also, equations for efficient calculation of system state probabilities and call blocking probabilities are derived. In Section IV, we present numerical examples for the evaluation of the proposed approach. Both analytical and simulation results are presented. In Section V, we briefly discuss the relevant works. We conclude and discuss our future work in Section VI.

II. SYSTEM DESCRIPTION AND ASSUMPTIONS

We consider a multirate CDMA system that accommodates K independent services. Calls of each service k ($k = 1, ..., K$) require a fixed data transmission rate R_k. Our considered system consists of a reference cell surrounded by neighbouring cells. We focus on the uplink direction only, i.e., calls from MUs to BS. Some notable models for the downlink of CDMA are [14], [15].

Below we present our assumptions on the traffic generated by MUs. Call inter-arrival times are exponentially distributed, forming Poisson traffic. The mean arrival rate for service k calls is denoted by λ_k. The requested service times are also assumed exponentially distributed. The mean service rate for a service k call is denoted by μ_k.

Hence, the offered traffic load in Erlangs (erl) for service k is calculated as follows [16]:

$$a_k = \frac{\lambda_k}{\mu_k} \tag{1}$$

We assume perfect power control at the BS. Therefore, the received power from each call of a particular service is the same. The received at the BS power from a service k call is denoted by P_k. Due to Multiple-Access Interference (MAI) of CDMA systems [17], signals generated by different MUs cause interference to each other. This is true for calls that reside in the same cell, as well as for calls that reside in neighbouring cells. Hence, we distinguish the intra-cell interference, I_{intra}, and the inter-cell interference, I_{inter}. In addition to that, the total interference, I_{total}, at the BS also includes the thermal noise, whose power is denoted as P_{noise}:

$$I_{total} = I_{intra} + I_{inter} + P_{noise} \quad (2)$$

We also assume that some of the in-service calls may not be active throughout the whole call duration. That is, a call may alternate between active (transmitting) and passive (idle) periods. To model this behaviour, we introduce the *activity factor* v_k ($0 < v_k \leq 1$) for each service k. The activity factor is defined as the ratio of the total duration of active periods over the whole call duration.

All calls in the system are distinguished into two following priority classes: *high priority* and *low priority*. The probability that a new call of service k is of high priority is denoted by p_k.

The priority class of a call is taken into account by the BS for the CAC decision upon the call arrival, as it will be discussed later. In typical CDMA systems, the CAC is performed by measuring the *noise rise*, NR, which is defined as in (3), and evaluating it against the predefined CAC threshold, NR_{max}, as in (4).

$$NR = \frac{I_{total}}{P_{noise}} \quad (3)$$

$$\begin{cases} \text{if } NR \leq NR_{max}, & \text{accept the call} \\ \text{if } NR > NR_{max}, & \text{block the call} \end{cases} \quad (4)$$

Note that in (4) the total interference, I_{total}, (implicitly included via NR) also includes the power, P_k, of the new call.

Also, note that, according to (2) and (3), NR takes values from $NR_{lower} = 1$ to $NR_{higher} = \inf$. In the first case, $I_{total} = P_{noise}$, which effectively means that the system is empty. In the second case, $I_{total} >> P_{noise}$, which effectively means that the interference from MUs is extremely high. Of course, when the CAC of (4) is applied, we have $NR_{higher} \leq NR_{max}$.

From the above, it is clear that the noise rise is not a suitable quantity to represent the CDMA system resources. Instead, the *cell load*, CL, defined in (5), is often used for such purposes [18].

$$CL = \frac{I_{total} - P_{noise}}{I_{total}} \quad (5)$$

where $0 \leq CL \leq 1$. Although, the theoretical upper bound for the cell load is 1 (when $P_{noise} \rightarrow 0$), in practice a typical upper bound is less than 1 and is, e.g., $n_{max} = 0.8$ [19].

By manipulating (3) and (5) we derive the following relation between the *cell load* and the *noise rise*:

$$CL = \frac{NR - 1}{NR} \quad (6)$$

Having adopted the cell load as the shared system resource, we now need to determine the resource requirements of a particular in-service call. One such suitable quantity is the call's *load factor*, defined in (7) for service k, which depends on the transmission rate, R_k, signal-to-noise ratio, SNR_k, and the carrier's chip rate, W.

$$LF_k = \frac{R_k SNR_k}{R_k SNR_k + W} \quad (7)$$

As it was discussed earlier, the distinction between priority classes is made during the CAC. To enable this, we define individual CAC thresholds for each class and also base the CAC decisions on the *cell load*, rather than on the *noise rise*, as in (4).

In particular, a service k high priority call is accepted if and only if the following CAC condition is satisfied:

$$LF_k + CL \leq CL_{max}^{HP} \quad (8)$$

where CL_{max}^{HP} is the CAC threshold for high priority calls.

Similarly, a service k low priority call is accepted if and only if the following CAC condition is satisfied:

$$LF_k + CL \leq CL_{max}^{LP} \quad (9)$$

where CL_{max}^{LP} is the CAC threshold for low priority calls.

Generally, $CL_{max}^{LP} \leq CL_{max}^{HP} = CL_{max}$.

III. Calculating Call Blocking Probabilities

A. Local Blocking Probabilities

Some part of total cell load, CL, is due to intra-cell MUs, denoted as CL_{intra}, whereas the rest is due to inter-cell MUs, denoted as CL_{inter}. That is:

$$CL = CL_{intra} + CL_{inter} \quad (10)$$

The intra-cell load can be easily determined by the BS, taking into account the number of MUs of each service and their corresponding load factors:

$$CL_{intra} = \sum_{k=1}^{K} U_k LF_k \quad (11)$$

where U_k is the number of service k MUs within the cell at a given time.

The exact determination of the inter-cell load, on the other hand, is not easy, as the BS is generally not aware about the number of MUs at the neighbouring cells and about their services. However, as it has been shown by previous studies, the inter-cell load can be very well modelled as a log-normal random variable with mean $\mu = E[CL_{inter}]$ and variance $\sigma^2 = VAR[CL_{inter}]$ [20]. The cumulative distribution function (CDF) of CL_{inter} with the aid of the well-known *error function*, erf(), is given by:

$$F(x) = \frac{1}{2}(1 + \text{erf}(\frac{\ln x - \mu}{\sigma\sqrt{(2)}})) \tag{12}$$

As it was discussed in Section II, the CAC at BS is based on (8), (9), and may block some of the arriving calls. In practice, however, the BS is explicitly aware of CL_{intra}, but not of CL or of CL_{inter}. Therefore, we express the probability of a call being blocked, as a function of CL_{intra}. This probability is called *Local Blocking Probability* (LBP) and is defined as follows, for high and low priority classes, respectively:

$$\begin{aligned} LBP_k^{HP}(CL_{intra}) = \Pr[CL_{intra} + CL_{inter} \\ + LF_k > CL_{max}^{HP}] \end{aligned} \tag{13}$$

$$\begin{aligned} LBP_k^{LP}(CL_{intra}) = \Pr[CL_{intra} + CL_{inter} \\ + LF_k > CL_{max}^{LP}] \end{aligned} \tag{14}$$

By performing some manipulations with (12), (13), and (14), we derive analytical expressions for LBPs in (15) and (16), below.

$$LBP_k^{HP}(CL_{intra}) = \begin{cases} 1 - F(x), & \text{for } x \geq 0 \\ 1, & \text{for } x < 0 \end{cases} \tag{15}$$

where $x = CL_{max}^{HP} - CL_{intra} - LF_k$.

$$LBP_k^{LP}(CL_{intra}) = \begin{cases} 1 - F(x), & \text{for } x \geq 0 \\ 1, & \text{for } x < 0 \end{cases} \tag{16}$$

where $x = CL_{max}^{LP} - CL_{intra} - LF_k$.

B. State Probabilities

As it was mentioned before, we consider the *cell load* as a shared system resource and the call's *load factor* as the resource requirement of a call. This approach enables us to describe the process of call arrivals and departures as a CTMC and to modify the K-R recursion for the calculation of *state probabilities* in CDTM systems.

Below we present the steps required for this modification. The discretization of CL_{max} and LF_k, required for the CTMC modelling, is performed with the use of the basic unit, g:

$$C = \frac{CL_{max}}{g}, b_k = \frac{LF_k}{g} \tag{17}$$

where C is the system capacity and b_k is the bandwidth requirement of a service k call, in the corresponding K-R recursion.

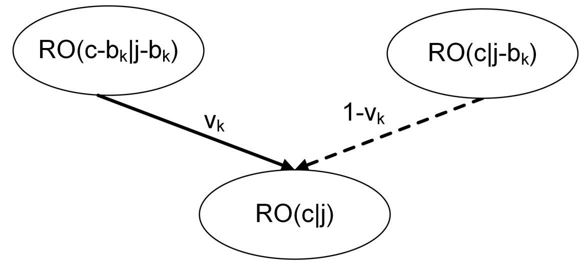

Fig. 1. Recursive calculation of the Resource Occupancy.

Let us denote by c the total number of occupied resources in the cell and by j the total number of resources occupied by active MUs. In the following, the parameter j will be considered as the system state. Let us also denote by $q(j)$ the probability of the state j.

The *resource occupancy*, $RO(c|j)$, is defined as the conditional probability that c resources are occupied in state j:

$$\begin{aligned} RO(c|j) = \sum_{k=1}^{K} RS_k(j)[v_k RO(c - b_k|j - b_k) \\ + (1 - v_k)RO(c|j - b_k)] \end{aligned} \tag{18}$$

for $j = 1, ..., j_{max}$ and $c \leq j$, with $RO(0|0) = 1$ and $RO(c|j) = 0$ for $c > j$, where v_k is the activity factor of service k calls and $RS_k(j)$ is the *resource share* of service k in a state j (which is defined in (20), below).

The basic concept behind the above recursive calculation of $RO(c|j)$ is given in Fig. 1. Assume that an active service k call arrives in the system. Recall that this will happen with probability v_k (since v_k is the activity factor). If at that time, $c - b_k$ resources are occupied in state $j - b_k$ (upper left circle), then both $c - b_k$ and $j - b_k$ will be increased by b_k. Hence, we will have the transition shown with the solid line. Assume now that a passive service k call arrives in the system. This will happen with probability $1 - v_k$. If at that time c resources are occupied in state $j - b_k$ (upper right circle), then only j will be increased by b_k. Hence, we will have the transition shown with the dashed line.

Due to the *inter-cell interference* of CDMA systems, blocking of call may theoretically happen at any state j. In the following, the probability of such call blocking is called *State Blocking Factor* (SBF). The SBF of service k in state j, can be calculated by summing LBPs over c and by multiplying with the corresponding ROs:

$$SBF_k(j) = \sum_{c=0}^{j} LBP_k(c)RO(c|j) \tag{19}$$

where $LBP_k(c) = LBP_k(CL_{intra})$ for $c = \frac{CL_{intra}}{g}$.

The *resource share*, $RS_k(j)$, mentioned in (18) above, of service k in a state j is defined as follows:

$$RS_k(j) = \frac{a_k(1 - SBF_k(j - b_k))b_k q(j - b_k)}{jq(j)} \tag{20}$$

This equation essentially shows the ratio of resources occupied by a particular service k over the total number of occupied resources in a given state j.

The un-normalized state probabilities can be calculated by extending the K-R recursion with LBFs for both high and low priority calls:

$$\hat{q}(j) = \frac{1}{j}\sum_{k=1}^{K}[p_k a_k(1 - LBF_k^{HP}(j - b_k)b_k\hat{q}(j - b_k)) + (1 - p_k)a_k(1 - LBF_k^{LP}(j - b_k)b_k\hat{q}(j - b_k))] \quad (21)$$

for $j = 1, ..., j_{max}$ and $\hat{q}(j) = 0$ for $j < 0$.

Finally, the normalized state probabilities are determined as follows:

$$q(j) = \frac{\hat{q}(j)}{\sum_{j=0}^{j_{max}} \hat{q}(j)} \quad (22)$$

C. Call Blocking Probabilities

The blocking probabilities of service k high priority calls can be calculated by adding all the state probabilities multiplied by the corresponding LBFs:

$$B_k^{HP} = \sum_{j=0}^{j_{max}} q(j)LBF_k^{HP}(j) \quad (23)$$

Similarly, the blocking probabilities of service k low priority calls can be calculated as follows:

$$B_k^{LP} = \sum_{j=0}^{j_{max}} q(j)LBF_k^{LP}(j) \quad (24)$$

IV. Numerical Examples

In this section, the analytical versus simulation results are compared in respect of blocking probabilities for both high and low priority calls. The simulation of the CDMA system has been performed using the Simscript III simulation tool [21]. Our aim is to evaluate two different services with the parameters as shown in Table I.

To obtain the simulation results, we generate 1M calls of the two services for both high and low priority classes. The CAC at the BS decides whether to accept or to block a new call according to the predefined CAC thresholds, as it was explained in Section II. We record the number of blocked calls and determine the call blocking probabilities. The presented simulation results are mean values of 8 repetitions with a confidence interval of 95%. In the figures, we present only the mean values, since the resultant reliability ranges are very small.

The presented analytical results are based on the formulae derived in Section III. The call blocking probabilities are eventually calculated from (23) and (24), for high and low priority calls, respectively. Recall, that in the aforementioned formulae, the incorporation of LBPs introduces some approximation errors. Hence, in order to estimate the impact of these approximations, comparison with simulation results is performed.

TABLE I. Service Parameters

	1st Service	2nd Service
Data Rate	$R_1 = 144$ Kbps	$R_2 = 384$ Kbps
Activity Factor	$v_1 = 0.7$	$v_2 = 0.6$
Signal-to-Noise Ratio	$SNR_1 = 3$ dB	$SNR_2 = 4$ dB
High Priority Calls Ratio	$p_1 = 1/6$	$p_2 = 1/3$

For the first service we initially generate traffic of 0.6 erl and then increase it up to 6 erl in steps of 0.6 erl (x-axis of Fig. 2). The high priority calls ratio for the first service is chosen to be $p_1 = 1/6$ (as it is also indicated in Table I). This effectively means that when the total traffic for the first service is 0.6 erl, then 0.1 erl corresponds to high priority calls. The remaining 0.5 erl corresponds to the low priority calls.

For the second service we initially generate traffic of 0.15 erl and then increase it up to 1.5 erl in steps of 0.15 erl (x-axis of Fig. 3). The high priority calls ratio for the second service is chosen to be $p_2 = 1/3$. That is, when the total traffic for the second service is 0.15 erl, then 0.05 erl corresponds to high priority calls, etc.

In Figs. 2 and 3, we present the analytical and simulation call blocking probabilities for the first and the second service, respectively. We observe that the accuracy of the proposed model is very good, since the analytical results are very close to simulation results in all cases. We also observe that, for both services, the blocking probabilities of high priority calls (denoted by HP in the figures) are significantly lower than the blocking probabilities of low priority calls (denoted by LP in the figures). This can be explained by different CAC thresholds used for high and low priority calls. In these experiments we used $CL_{max}^{HP} = CL_{max} = 0.8$ and $CL_{max}^{LP} = 0.7$.

Next, we performed some experiments by varying the CAC thresholds of low priority calls and observe the impact on the blocking probabilities of high priority calls. The results for four different CAC thresholds of the first service are presented in Fig. 4. We observe, that when the offered traffic is low (e.g., up to 3 erl), varying the CAC thresholds of low priority calls would have very negligible impact on the performance of high priority calls. On the other hand, when the offered traffic is high (especially if over 5 erl) and the probability of congestion is quite high, then by lowering the CAC thresholds (e.g., from 0.75 to 0.6) would significantly reduce the blocking probability of high priority calls.

V. Relevant Works

A number of teletraffic models have been proposed for the calculation of cell capacity and call blocking probabilities in cellular CDMA networks. In [18], the calculation of call blocking probabilities in W-CDMA systems is based on an extension of the K-R recursion. The authors consider Poisson call arrival process in the uplink direction and fixed cell resource requirements. The accuracy of the introduced approximations is verified via simulations. This work was extended in [22] and [19] by incorporating into the model the quasi-random call

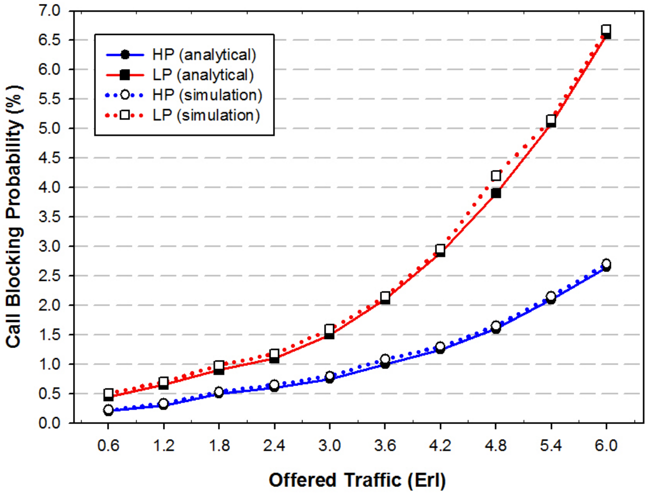

Fig. 2. Call blocking probabilities vs offered traffic for the 1st service.

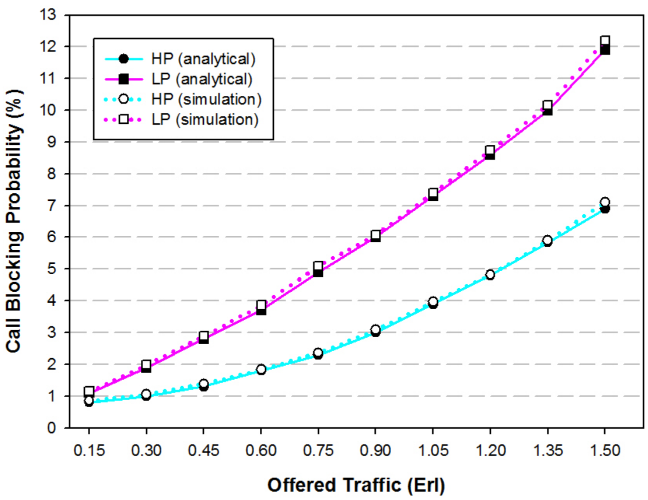

Fig. 3. Call blocking probabilities vs offered traffic for the 2nd service.

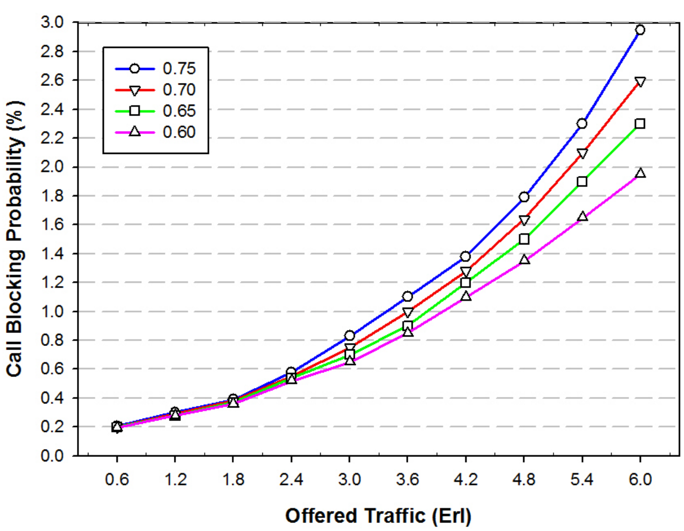

Fig. 4. Blocking probablity of high priority calls vs offered traffic, for different CAC thresholds of low priority calls (1st service).

arrival process. This assumption is more realistic, especially in the case of small cells.

The aforementioned works consider only unicast connections. An analytical model for multi-service cellular networks servicing multicast connections has been proposed in [23] and has been extended further with traffic engineering mechanisms in [24]. The model of [19] has been extended in [25] to incorporate elastic and adaptive services, where arriving calls may request for less bandwidth if the cell is congested. Another extension that considers batched Poisson input traffic in CDMA networks is proposed in [26].

There have also been efforts to analytically model interference cancellation schemes in CDMA systems [27], [28], [29]. In [30], the performance of W-CDMA networks supporting different QoS requirements has been evaluated. The authors derive accurate approximations for 3G systems and beyond. In [31], an accurate system model for a W-CDMA cell with finite number of channels and quasi-random traffic input is proposed.

Some of the aforementioned models have been extended to explicitly incorporate the handoff traffic. An analytic model for W-CDMA networks with soft handoff mechanisms has been proposed in [32]. The proposed model is based on the fixed point methodology and dynamic reservation, under the assumption that some part of the cell resources will be dedicated for servicing handoff traffic. In [33], the soft handover is modelled by constructing the so-called *active set* of cells that participate in the handoff process having the best signal-to-noise ratio. In [34], the model considering handoff blocking probabilities and finite source population is proposed and evaluated. The model assumes a multi-service CDMA system and determines local blocking probabilities of arriving calls at different system states.

Regarding the priority-based CAC in cellular systems, there have been a few notable works. In [35], a balanced radio resource allocation scheme for OFDMA systems is proposed. The authors use adaptive priority thresholds to enhance system's throughput and to provide QoS guarantee to MUs. In [36], a distributed priority-based CAC is proposed for cellular networks. The distinction into high and low priority users is based on the target SNRs. Also, the simulation experiments confirm good adaptation properties of the proposed algorithm in highly dynamic scenarios and under the presence of user mobility. However, none of the aforementioned works considers the peculiarities of CDMA systems when modelling the priority traffic classes.

VI. Conclusion and Future Work

In this paper, we propose a novel modelling approach for priority-based cellular CDMA systems. We assume Poisson arriving calls and multirate traffic. We explicitly model different calls' priority classes, which impact the call admission control decisions at the base station. The proposed model results in efficient and recursive formula for the calculation of system state probabilities. Which, in the end, enables us to determine the call blocking probabilities of different services and of different priority classes. Since the modelling approach is based on a number of approximations, we verify its accuracy via simulation experiments. We also study the impact of different call admission control thresholds on the blocking probabilities of high priority calls.

In our future work, we plan to investigate other, non-Poisson call arrival processes, such as the quasi-random process. We also plan to incorporate into our model the notion of elastic traffic, where calls compress/expand their required bandwidth depending on the traffic conditions in the reference cell as well as in neighbouring cells.

REFERENCES

[1] F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. M. Aggoune, and H. Haas, "Cellular architecture and key technologies for 5G wireless communication networks," IEEE Communications Magazine, Feb. 2014, pp. 122-130.

[2] W. C. Lee, "Overview of cellular CDMA," IEEE Transactions on Vehicular Technology, vol. 40, no. 2, 1991, pp. 291-302.

[3] S. Patel, C. Malhar, and K. Kapadiya, "5G: future mobile technology - vision 2020," International Journal of Computer Applications, vol. 54, no. 17, 2012, pp. 6-10.

[4] S. Chen and J. Zhao, "The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication," IEEE Communications Magazine, vol. 52, no. 5, 2014, pp.36-43.

[5] Z. Wang, S. Fan, and Y. Rui, "CDMA-FMT: A novel multiple access scheme for 5G wireless communications," Proc. 19th International Conference on Digital Signal Processing, Hong Kong, August 2014.

[6] O. Tipmongkolsilp, S. Zaghloul, and A. Jukan, "The evolution of cellular backhaul technologies: Current issues and future trends," IEEE Communications Surveys & Tutorials, vol. 13, no. 1, 2011, pp. 97-113.

[7] "Intelligent base stations," White Paper, Nokia Siemens Networks, 2012.

[8] Z. Zaidi, V. Friderikos, and M. A. Imran, "Future RAN architecture: SD-RAN through a general-purpose processing platform," IEEE Vehicular Technology Magazine, vol. 10, no. 1, 2015, pp. 52-60.

[9] V. G. Vassilakis, I. D. Moscholios, A. Bontozoglou, and M. D. Logothetis, "Mobility-aware QoS assurance in software-defined radio access networks: An analytical study," Proc. 1st IEEE Workshop on Software-Defined 5G Networks (Soft5G), London, United Kingdom, April 2015.

[10] S. Andreev, A. Pyattaev, K. Johnsson, O. Galinina, and Y. Koucheryavy, "Cellular traffic offloading onto network-assisted device-to-device connections," IEEE Communications Magazine, vol. 52, no. 4, 2014, pp. 20-31.

[11] V. G. Vassilakis, G. A. Kallos, I. D. Moscholios, and M. D. Logothetis, "Evaluation of a call admission control scheme in W-CDMA cellular networks," Proc. 6th IEEE CSNDSP, Graz, Austria, July 2008.

[12] J. S. Kaufman, "Blocking in a shared resource environment," IEEE Transactions on Communications, vol. 29, no. 10, 1981, pp. 1474-1481.

[13] J. W. Roberts, "A service system with heterogeneous user requirements," In: G. Pujolle (Ed.), Performance of Data Communications Systems and Their Applications, North Holland, Amsterdam, 1981, pp. 423-431.

[14] A. Mäder and D. Staehle, "Analytic modeling of the WCDMA downlink capacity in multi-service environments," Proc. 16th ITC specialist seminar, Antwerp, Belgium, September 2004.

[15] I. B. Daskalopoulos, V. G. Vassilakis, and M. D. Logothetis, "Thorough analysis of downlink capacity in a WCDMA cell," Proc. 1st International Conference on Mobile Lightweight Wireless Systems (MOBILIGHT), Athens, Greece, May 2009.

[16] H. Akimaru, "Teletraffic: theory and applications," Springer Publishing Company, 2012.

[17] J. Zhang and T. Konstantopoulos, "Multiple-access interference processes are self-similar in multimedia CDMA cellular networks," IEEE Transactions on Information Theory, vol. 51, no. 3, 2005, pp. 1024-1038.

[18] D. Staehle and A. Mäder, "An analytic approximation of the uplink capacity in a UMTS network with heterogeneous traffic," Proc. 18th International Teletraffic Congress (ITC), Berlin, Germany, September 2003.

[19] V. G. Vassilakis, G. A. Kallos, I. D. Moscholios, and M. D. Logothetis, "The wireless Engset multi-rate loss model for the call-level analysis of W-CDMA networks," Proc. 18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Athens, Greece, September 3-7, 2007, pp. 1-5.

[20] G. A. Kallos, V. G. Vassilakis, I. D. Moscholios, and M. D. Logothetis, "Performance modelling of W-CDMA networks supporting elastic and adaptive traffic," Proc. 4th HET-NETs 2006, Ilkley, United Kingdom, September 2006.

[21] Simscript III, http://www.simscript.com [May 2015].

[22] M. Stasiak, A. Wisniewski, P. Zwierzykowski, and M. Glabowski, "Blocking probability calculation for cellular systems with WCDMA radio interface servicing PCT1 and PCT2 multirate traffic," IEICE Transactions on Communications, vol. E92-B, no. 4, 2009, pp. 1156-1165.

[23] D. Parniewicz, M. Stasiak, and P. Zwierzykowski, "Analytical model of the multi-service cellular network servicing multicast connections," Telecommunication Systems, Springer, vol. 52, no. 2, 2011, pp. 1091-1100.

[24] D. Parniewicz, M. Stasiak, and P. Zwierzykowski, "Traffic engineering for multicast connections in multiservice cellular networks," IEEE Transactions on Industrial Informatics, vol. 9, no. 1, 2013, pp. 262-270.

[25] V. G. Vassilakis, G. A. Kallos, I. D. Moscholios, and M. D. Logothetis, "Call-level analysis of W-CDMA networks supporting elastic services of finite population," Proc. IEEE International Conference on Communications (ICC), Beijing, China, May 2008.

[26] I. D. Moscholios, G. A. Kallos, V. G. Vassilakis, and M. D. Logothetis, "Congestion probabilities in CDMA-based networks supporting batched Poisson input traffic," Wireless Personal Communications, vol. 79, no. 2, November 2014, pp. 1163-1186.

[27] G. A. Kallos, V. G. Vassilakis, and M. D. Logothetis, "Call-level performance analysis of a W-CDMA cell with finite population and interference cancellation," European Transactions on Telecommications, vol. 22, no. 1, 2011, pp. 25-30.

[28] I. D. Moscholios, M. A. Katsiva, G. A. Kallos, V. G. Vassilakis, and M. D. Logothetis, "Equalization of congestion probabilities in a W-CDMA cell supporting calls of finite sources with interference cancellation," Proc. 9th IEEE/IET CSNDSP, Manchester, United Kingdom, July 2014.

[29] I. D. Moscholios, G. A. Kallos, M. A. Katsiva, V. G. Vassilakis, and M. D. Logothetis, "Call Blocking Probabilities in a W-CDMA cell with interference cancellation and bandwidth reservation," Proc. IEICE Information and Communication Technology Forum (ICTF), Poznan, Poland, 2014, pp. 28-30.

[30] M. Ivanovich and P. Fitzpatrick, "An accurate performance approximation for beyond 3G wireless broadband systems with QoS," IEEE Transactions on Vehicular Technology, vol. 62, no. 5, 2013, pp. 2230-2238.

[31] G. A. Kallos, V. G. Vassilakis, and M. D. Logothetis, "Call blocking probabilities in a W-CDMA cell with fixed number of channels and finite number of traffic sources," Proc. 6th IEEE International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Graz, Austria, July 23-25, 2008, pp. 200-203.

[32] M. Stasiak, P. Zwierzykowski, and D. Parniewicz, "Modelling of the WCDMA interface in the UMTS network with soft handoff mechanism," Proc. IEEE GLOBECOM-2009, Honolulu, USA, December 2009.

[33] S. Hanczewski, M. Stasiak, and P. Zwierzykowski, "A new model of the soft handover mechanism in the UMTS network," Proc. 9th IEEE/IET CSNDSP, Manchester, United Kingdom, July 2014.

[34] V. G. Vassilakis and M. D. Logothetis, "The wireless Engset multirate loss model for the handoff traffic analysis in W-CDMA networks," Proc. 19th IEEE PIMRC, Cannes, France, September 2008.

[35] Y.-H. Chung and C.-J. Chang, "A balanced resource scheduling scheme with adaptive priority thresholds for OFDMA downlink systems," IEEE Transactions on Vehicular Technology, vol. 61, no. 3, 2012, pp. 1276-1286.

[36] M. Rasti and E. Hossain, "Distributed priority-based power and admission control in cellular wireless networks," IEEE Transactions on Wireless Communications, vol. 12, no. 9, 2013, pp. 4483-4495.