

# Multi-application packetized traffic model of single source for next generation IP-based mobile systems

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*Abstract*— In this paper we propose a cross-layer integrated model of traffic generated by a single user for next generation (NG) All-IP networks. Our model is multi-application one and basically integrates two parts: mobility model and teletraffic model. The mobility part captures mobility behavior of single user and modelled by a Markov chain with finite state space. Teletraffic part depends on both mobility of the user and active application, captures teletraffic characteristics of different applications at both session and packet levels and represented by a superposition of Markov chain and discrete-time batch Markovian arrival process (D-BMAP). Mobility and various teletraffic parts are integrated, so that the whole model can be seen as triply stochastic process while does not lead outside D-BMAP framework. This is due to special integration of parts, which makes teletraffic models to be functions of mobility one. Analysis of behavior of proposed model indicates that even in presence of cross-correlation between mobility of the user and its teletraffic demands it is still possible to estimate actual packet level traffic demands posed on NG All-IP networks by a single user.

*Keywords*— NG All-IP, teletraffic model, mobility model, cross-layer integrated traffic model.

## I. INTRODUCTION

UP to date the Internet and wireless communications have been evolved as separate technologies because of different types of traffic they were intended for. However, nowadays the convergence of these technologies is getting clear. This process is stimulated by widespread grow of both the Internet and mobile communication systems along with users that wish to access Internet services 'anytime and anywhere'.

While next generation mobile systems are not clearly defined, there is a common agreement that these networks will rely on IP protocol as an end-to-end transport technology. The motivation is to have a common service platform for future composite 'mobile Internet' known as next generation (NG) All-IP networks.

In addition to broadband wireless access to the Internet, NG All-IP mobile systems should be able to provide quality of service (QoS) to their applications. However, inherent characteristics of mobile systems, like users' mobility, their teletraffic demands and unstable nature of the air interface have to be addressed before a required quality of user services will be achieved. These new challenges require develop-

ment of new methods of teletraffic theory, optimization and design. Among others, the special attention should be paid to novel traffic modelling techniques.

Due to circuit switching technology utilized by second generation (2G) mobile systems, their performance characteristics are typically limited to call (session) level performance parameters like new call blocking, handover call blocking etc. Correspondingly, traffic models designed for 2G systems are primarily concerned with capturing call level parameters of traffic sources. NG All-IP networks are assumed to be based on packet-switching technology, and therefore, mobile users may not occupy constant bandwidth during a whole duration of a session. Therefore, these systems should potentially benefit from statistical multiplexing at the network layer. It is well known from experience obtained in wired networks that due to statistical multiplexing a small fraction of users that use bandwidth-greedy applications may easily produce a bottleneck at the wireless link. Therefore, dealing with wireless access in addition to call level performance characteristics we have to provide packet level guarantees. Due to these reasons, the focus of users' traffic modelling should be extended to include packet and call level models of single user. These models are useful to study the performance of the network and to predict the QoS expectations that a particular applications may experience at different levels of wireless link congestion and different levels of channel quality.

A survey of research papers have shown that most traffic models designed for 2G mobile systems do not take into account mobility behavior of single user. Indeed, those models assume a stationary behavior of large population of users and try to capture call level parameters by distributions like exponential one or its mixtures (see [1], [2] and references therein). However, once we have to consider user in isolation, the assumption of stationary characteristics of large population should be dropped. Indeed, stationary call level characteristics, while were shown to be a fair predictors of large populations, are not appropriate for single user, where the mobility behavior may significantly affect call level traffic demands, and as a result, packet level characteristics.

To date the only example of traffic model, which simultaneously captures mobility behavior and network layer (packet level) teletraffic demands of single user, is a study presented by Antunes *et. al* [3]. Based on general assumptions regarding teletraffic and mobil-

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ity of the user, they propose to use a combination of Markovian arrival processes (MAP), one of which describes the mobility behavior while another one specifies call level teletraffic demands. Despite obvious benefits, that model is quite complex, and therefore, restricts its usage in performance evaluation of NG All-IP networks.

In this paper we develop a cross-layer integrated traffic model of packetized variable bit rate (VBR) traffic source for NG All-IP mobile networks. Our model is multi-application one and basically integrates two parts: mobility model and teletraffic model. The mobility part captures mobility behavior of single user and modelled by a Markov chain with finite state space. Teletraffic part depends on both mobility of the user and active application, captures teletraffic characteristics of different applications at both session and packet levels and represented by a superposition of Markov chain and discrete-time batch Markovian arrival process (D-BMAP). Mobility and various teletraffic parts are integrated, so that the whole model can be seen as triply stochastic process while does not lead outside D-BMAP framework. This is due to special integration of parts, which makes teletraffic models to be functions of mobility one.

Our paper is organized as follows. We make necessary remarks on traffic modelling issues for NG All-IP networks in Section II. In Section III we consequently define mobility model, call level teletraffic model and packet level teletraffic model. We integrate them into one composite model in Section IV. Behavior of the model is considered in Section V. Extension to multiple applications is given in Section VI. In Section VII we give examples of proposed model. Conclusions and further work is outlined in last section.

## II. TRAFFIC MODELLING FOR NG ALL-IP SYSTEM

### A. Mobility and call level teletraffic demands

To illustrate the influence of user's mobility on its teletraffic demands let us define two classes of user's mobility behavior. In accordance with such simple classification a mobile user can be in one of the following states:

- Fixed;
- Nomadic.

Assume that when a mobile user is in the fixed state it uses network services with probability  $p^F$ ,  $p^F \in (0, 1)$ , and with probability  $(1 - p^F)$  stays idle. Similarly, when mobile user is on move it accesses services with probability  $p^N$ ,  $p^N \in (0, 1)$ , and does not use the network with complementary probability  $(1 - p^N)$ . Indices  $F$  and  $N$  stand for fixed and nomadic states respectively. In this subsection we explain why it is necessary to assume that the call level traffic demands depend on the mobility of the user which may lead to the case  $p^F \neq p^N$ .

To date voice service has been a dominating application in 2G mobile systems. Due to physiological tests the aural impression of information does not require too much attention (up to 20%), and therefore,

the moving user is aware of the situation around even when moving (driving, walking etc.). Therefore, to date one could assume  $p^F = p^N$ .

The situation changes with the introduction of multimedia services. For example, the visual information gives us more than 80% percent of overall information. Moreover, the combination of aural and visual information dominates with overall percentage up to 97%, and therefore, affects our attention significantly. When the aural information is presented in conjunction with other medias it is fair to assume that moving users will not use such services frequently. It leads to the case  $p^F \neq p^N$  and dependence between mobility and call level teletraffic demands is evident. Additionally, in some countries there are already restrictions imposed on usage of mobile phones when driving. It is also leads to the case  $p^F \neq p^N$  even for 2G systems. It may be the case that if one does not take into account this dependence the necessary capacity of the system may be overestimated or underestimated which leads to one of the undesirable effects: unwarranted investments or unsatisfactory service quality.

We have to note that both  $p^F$  and  $p^N$  implicitly define user's traffic demands at the call level, and therefore, traffic demands at the packet level. Additionally, the dependence of traffic demands on mobility behavior cannot be generally represented by deterministic functional relationship but has a probabilistic nature. In what follows, we assume that the user's call level teletraffic demands are probabilistic function of user's mobility.

Additionally, we cannot assume that parameters  $p^F$  and  $p^N$  are stationary. Indeed, based on experience obtained from telephone networks [4] we can state that they changes over several timescales depending on the time of the day, day of the week etc. However, given a certain (relatively small) timescale of interest we can expect a stationary behavior of  $p^F$  and  $p^N$ . In what follows we restrict our attention to such timescale at which  $p^F$  and  $p^N$  are expected to be stationary like time consistent busy our (TCBH).

### B. Call level and packet level teletraffic demands

3G mobile systems, which were recently given a lot of attention, can be nowadays seen as an intermediate step between conventional 2G mobile systems and NG All-IP networks. Due to the circuit-switched technology utilized by 2G systems, the user of a mobile system is granted with a constant bit rate channel during the cell dwell time (time for which a particular user stays in a certain cell). When a free channel is not available, the user is forced to leave the system. Handover calls between cells are served almost similarly: the handover call to a new cell is assigned one of the free channels during the cell dwell time. If all channels in the new cell are busy (including those ones specifically designed for handover calls), the handover call is terminated. Therefore, QoS provided to users by 2G mobile systems is typically limited to call level parameters like new call blocking, handover call blocking

etc. Correspondingly, traffic models designed for 2G systems are primarily concerned with capturing call level parameters of traffic sources.

NG All-IP networks are supposed to use packet-switching technology, and therefore, one can expect that all calls, including voice ones, will be IP based and require different, often variable bit rates. Thus, dealing with NG All-IP networks in addition to call level QoS parameters we have to provide IP level QoS guarantees like bounds on packet losses, delays, delay jitter etc. To characterize performance of user services in NG All-IP networks, user's traffic models which simultaneously captures both call level and packet level teletraffic characteristics are needed.

An example of correspondence between call level and packet level teletraffic demands for simple voice codec with silence suppression capabilities is shown in Fig. 1, where black rectangles denote the talkspurt periods. One can note that there is a strict correspondence between the calling activity of the user and its packetized traffic i.e. when the session is off no packet are generated, while when the session is on packets are generated according to a suitable model. Additionally, we have to note that the parameters of packet source depends on the type of the source only and do not directly depend on mobility behavior of the user. Therefore, we assume that these parameters are constant every time the session is on irrespective of mobility state of the user.

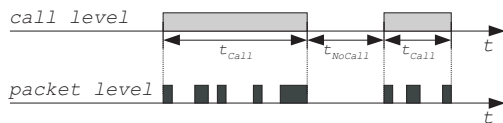


Fig. 1. An example of correspondence between call level and packet level teletraffic demands.

### III. MOBILITY AND TELETRAFFIC MODELS

#### A. Mobility model

Assume the same granularity of user's mobility classes as in Section II-B, and set  $p^F \neq p^N$ . Extension to the case of more general mobility is straightforward.

Consider a discrete-time environment i.e. assume that time axis is slotted with certain granularity  $\Delta = (t_{i+1} - t_i)$ ,  $i = 0, 1, \dots$ , and changes of mobility state of the user are only allowed at slot boundaries. Considering the real mobility behavior of the user one can expect some type of positive correlation between state changes. Roughly speaking, if the user is in the nomadic state (fixed) at the slot  $i$  it is more likely it will stay in nomadic (fixed) state at the slot  $i + 1$ . In this paper we propose to capture such type of autocorrelation by a Markov chain with two states.

Consider a discrete-time homogenous irreducible and aperiodic Markov chain  $\{S^M(n), n = 0, 1, \dots\}$  defined at the state space  $S^M(n) \in \{1, 2\}$ , where superscript  $M$  stands for mobility, state 1 corresponds to fixed state and state 2 denotes nomadic state. Let  $P^M$

be transition matrix of this Markov chain:

$$P^M = \begin{pmatrix} p_{11}^M & p_{12}^M \\ p_{21}^M & p_{22}^M \end{pmatrix}. \quad (1)$$

In accordance with proposed model, time, user spends in both states (fixed and nomadic), are geometrically distributed with corresponding parameters (1) and can only be changed at slot boundaries.

For our simple model the autocorrelation of user's mobility is geometrically distributed with parameter  $\lambda_2^M$ , where  $\lambda_2^M$  is the non-unit eigenvalue of  $P^M$  ( $\lambda_1^M$  is always one since  $P^M$  is the one-step transition matrix of discrete-time homogenous ergodic Markov chain).

One should note that the model can be extended to capture more general distributions of sojourn times including sum of geometrical, hypergeometrical and discrete-time phase distributions. This can be done by allowing more than one state of the Markov chain to denote each mobility state of the user. However, the minimum time the user stays in arbitrary state is still  $\Delta$ . So that the careful choice of  $\Delta$  is of high importance.

One may also define more general granularity of user's mobility behavior. For example three-states Markov chain with fixed, walking, driving states can be easily defined. However, while the correlation between two-states mobility and usage of the network is evident, comprehensive statistical studies are needed to judge whether it is necessary to use more general granularity.

Note that the underlying assumption of the proposed model is that the mobility of user is *independent* of its teletraffic demands. This, however, may not hold in certain cases. Generalization of our model to traffic dependent mobility behavior is out of the scope of this paper.

#### B. Call level teletraffic model

So far we have defined two mobility states: fixed and nomadic. Let us consequently define call level teletraffic models for each of those states.

Consider the fixed state. Assume that when the mobile user is in the fixed state it is in the calling mode (session is on) with probability  $p_{11}^F$ ,  $p_{11}^F \in (0, 1)$ , and with probability  $p_{12}^F$ , switches to idle mode, where  $p_{12}^F = (1 - p_{11}^F)$ , i.e. time period user stays in calling mode is geometrically distributed. Additionally, assume that the user stays idle with probability  $p_{22}^F$ ,  $p_{22}^F \in (0, 1)$ , and with complementary probability  $p_{21}^F$ ,  $p_{21}^F = (1 - p_{22}^F)$ , switches to calling mode.

These probabilities constitute a simple Markov chain with two states as follows. Consider a discrete-time, homogenous, irreducible and aperiodic Markov chain  $\{S^F(n), n = 0, 1, \dots\}$  defined at the state space  $S^F(n) \in \{1, 2\}$ , where superscript  $F$  stands for fixed state, state 1 denotes a calling state and state 2 – idle state. Let  $P^F$  be transition matrix of the Markov chain:

$$P^F = \begin{pmatrix} p_{11}^F & p_{12}^F \\ p_{21}^F & p_{22}^F \end{pmatrix}. \quad (2)$$

One can note that in accordance with our model session and idle times are geometrically distributed with corresponding parameters (2). Similarly to mobility model we can generalize these sojourn times to arbitrary mixture of geometrical components.

Given assumptions of geometrically distributed sojourn times in calling and idle states we define a discrete-time, homogenous, ergodic Markov chain  $\{S^N(n), n = 0, 1, \dots\}$  for nomadic behavior of the user governed by transition probability matrix  $P^N$ :

$$P^N = \begin{pmatrix} p_{11}^N & p_{12}^N \\ p_{21}^N & p_{22}^N \end{pmatrix}. \quad (3)$$

In accordance with our assumptions, both call level teletraffic models presented here should be a probabilistic functions of user's mobility behavior.

### C. Packet level model

There are a lot of packet level traffic models developed for wired networks, each of which targeted on certain type of source. In our paper we assume that the packet arrival process from VBR source is represented by discrete-time batch Markovian arrival process (D-BMAP) with two states of underlying Markov chain.

The reason to use D-BMAP is twofold. Firstly, D-BMAP allows extensions to complex VBR traffic sources. For example, it has been shown that voice, video and data traffic can be reasonably well represented by D-BMAP [5], [6], [7]. Secondly, the queuing of D-BMAP is well studied, and general results have already been obtained [8], [9], [10]. Therefore, D-BMAP allows to preserve analytical tractability.

Consider a discrete-time, homogenous, ergodic Markov chain  $\{S^P(n), n = 0, 1, \dots\}$  defined at the state space  $S^P(n) \in \{1, 2\}$ . Let  $P^P$  be transition matrix of the Markov chain. Let then  $\{W^P(n), n = 0, 1, \dots\}$  be the D-BMAP arrival process whose underlying Markov chain is  $\{S^P(n), n = 0, 1, \dots\}$ . We define D-BMAP as a sequence of matrices  $D^P(k)$ ,  $k = 0, 1, \dots$ , each of which contains probabilities of transition from state to state with  $k = 0, 1, \dots$  arrivals respectively:

$$d^P(k)_{ij} = Pr\{W^P(n) = k, S^P(n) = j | S^P(n-1) = i\}, \quad (4)$$

where  $k = 0, 1, \dots$ , and  $i, j \in \{1, 2\}$  are conditional probability distribution functions of D-BMAP.

One may note that in accordance with definition, it is allowed for D-BMAP to have different conditional probability distribution functions for each different pair of states. However, for our model we allow only those arrivals, when the state of modulating Markov chain changes from 1 to 1. Probabilities of other arrivals are set to zero. Therefore, we have an ON-OFF process widely used for VBR traffic modelling. We have to note that parameters of this process are stationary ones, should depend on the type of the source only and should not directly depend on the mobility

of the user. It means that anytime when the session level model is in the ON state packet should be generated according to D-BMAP process, while when the session is off no packet are generated.

## IV. INTEGRATED MODEL

Firstly, in this section we integrate model of user's mobility behavior and model of call level traffic demands. In fact, we make mobility and call level teletraffic models to be a parts of composite model in accordance with analytical paradigm proposed in [11]. Then using the same paradigm we add a packet level teletraffic model to already obtained integrated call level traffic model.

### A. Call level integrated model

In accordance with our assumptions, previously defined call level teletraffic models should be a probabilistic functions of user's mobility:

$$S^C(n) = f_{Pr}(S^M \in \{1, 2\}), \quad (5)$$

where  $S^C(n)$  is the state of composite model at the call level and index  $Pr$  denotes probabilistic relationship. Therefore, the choice of appropriate call level teletraffic model should depend on current mobility state of the user:

$$\begin{aligned} \{S^I(n), n = 0, 1, \dots\} = \\ = \begin{cases} \{S^F(n), n = 0, 1, \dots\}, & S^M = 1, \\ \{S^N(n), n = 0, 1, \dots\}, & S^M = 2. \end{cases} \end{aligned} \quad (6)$$

Assume that call level teletraffic demands of the user is generated according to Markov chains presented in Section III-B and choice of the model depends on mobility state of the model presented in Section III-A. It means that the choice of transition probabilities of Markov chains of integrated model must depend on the state of mobility model as follows:

$$p_{i,j}^T = \begin{cases} p_{ij}^F, & i, j \in \{1, 2\}, S^M(n) = 1, \\ p_{ij}^N, & i, j \in \{1, 2\}, S^M(n) = 2. \end{cases} \quad (7)$$

Note that  $p_{ij}^N, p_{ij}^F, i, j \in \{1, 2\}$  are different as far as they belong to different Markov chains. Therefore, session times as well as idle times are differently distributed in fixed and nomadic states.

Given that Markov chains representing call level teletraffic demands and associated with states of Markov chain of the mobility model have the same number of states (two in our case), the Markov chain of integrated model can now be defined on the state space  $S^I$  as follows:

$$S^I \in \{(1, 1), (1, 2), (2, 1), (2, 2)\}, \quad (8)$$

where the first number in state description denotes the state of the mobility model while the second one is the state of corresponding call level teletraffic model.

Note that actually in (8) we still deal with one dimensional Markov chain. To show it we can just re-enumerate the state space of resulting model. However, state description given by pairs  $(i, j)$ ,  $i, j \in \{1, 2\}$  is simply more convenient to remember that the call level integrated model is just a superposition of mobility model and teletraffic ones.

In (8), an appropriate call level teletraffic model should only be associated with those states of the mobility model which correspond to the appropriate mobility state. Finally, transition probability matrix of the Markov chain of integrated model is given by Kronecker product:

$$P^I = \begin{pmatrix} (1, 1) & (1, 2) & (2, 1) & (2, 2) \\ (1, 1) & p_{11}^M p_{11}^F & p_{11}^M p_{12}^F & p_{12}^M p_{11}^F & p_{12}^M p_{12}^F \\ (1, 2) & p_{11}^M p_{21}^F & p_{11}^M p_{22}^F & p_{12}^M p_{21}^F & p_{12}^M p_{22}^F \\ (2, 1) & p_{21}^M p_{11}^F & p_{21}^M p_{12}^F & p_{22}^M p_{11}^F & p_{22}^M p_{12}^F \\ (2, 2) & p_{21}^M p_{21}^F & p_{21}^M p_{22}^F & p_{22}^M p_{21}^F & p_{22}^M p_{22}^F \end{pmatrix}. \quad (9)$$

Our call level integrated traffic model, which is actually represented one-dimensional Markov chain, is simply a probabilistic function of Markovian model of user's mobility. So that the whole traffic model can be seen as doubly stochastic process while does not lead outside one-dimensional Markov chain framework. It is also clear, that those cases when there are non-probabilistic functional relationships between mobility behavior and teletraffic demands are the special cases of the model presented here.

Additionally, we have to recall that the definition of our integrated model can be extended by allowing more general models of both mobility behavior and call level teletraffic demands. However, when defining such models one have to note that due to the Kronecker product of transition probability matrices the state space of resulting Markov chain of integrated model grows fast.

### B. Packet level integrated model

Assume that the user's packet traffic is generated according to D-BMAP model presented in Section III-C.

To integrate the packet level model to already obtained composite call level model we assume that each state of that model is the microstate of new one as shown in Fig. 2.

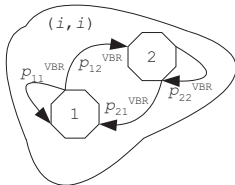


Fig. 2. Macrostate of packet level integrated traffic model.

Note that these additional states representing packetized traffic are only required in those states of inte-

grated call level model in which the state of call level part is 1 (session is on). However, it is not possible to integrate these states without new parameterizing of resulting Markov chain.

To avoid parameterization problem we propose to superpose call level integrated model obtained earlier and D-BMAP model of packetized source. Indeed, it is possible since both models have Markovian structure. In accordance with superposition, states of packet level teletraffic model are integrated to *each state* of call level integrated model and the state space of new superposed model is:

$$S_{VBR}^I = ((1, 1, 1), \dots, (1, 2, 2), (2, 1, 1), \dots, (2, 2, 2)), \quad (10)$$

where the first number is the state of mobility model, second one is the state of call level teletraffic model and the last one – state of packet level teletraffic model.

To get transition probabilities of new integrated packet level model we have to define Kronecker product of transition probability matrices of call level integrated model and underlying Markov chain of D-BMAP process modelling VBR packetized traffic. At the last step we have to set all probabilities of arrivals when the Markov chain change its state to and from other states, than those of the set  $\{(i, j, 1)\}$ ,  $i, j \in \{1, 2\}$ , to zero. We have to note that despite triple description of states (10) we are given a D-BMAP process.

Extension to the case of more complicated packetized traffic is also possible. However, since the complexity of the whole model depends on the complexity of the packetized traffic source, the limiting factor is the state space of underlying Markov chain of resulting model.

## V. BEHAVIOR OF PROPOSED MODEL

Transition diagram of the call level integrated model is shown in Fig. 3. One can note that any state of the proposed model can be reached from any other state with probability, expressed through transition probabilities of each part of the model. Additionally, there are no restrictions imposed by mobility of the user on its calling activity except for underlying stochastic modulation.

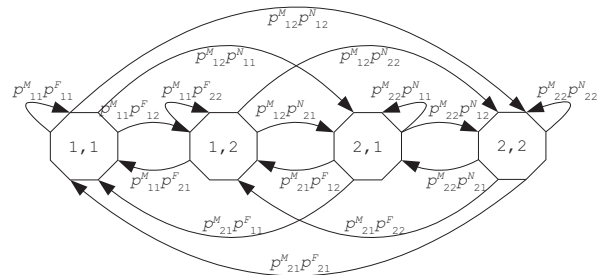


Fig. 3. Transition diagram of the call level integrated model.

To illustrate behavior of the model let us firstly consider its microscopic behavior presented in Fig. 4. Recall that our model is discrete-time and slot duration is  $\Delta$ . Additionally, slots of teletraffic and mobility models are synchronized and equal to each other. Assume that the model is in the state (1, 1) at the  $n^{\text{th}}$  time slot, which means that the session is active and the user is in the fixed state. In accordance with our model the session completion rate in this state is  $p_{12}^F = (p_{11}^M p_{12}^F + p_{12}^M p_{12}^N)$ , while change to nomadic state can occur with rate  $p_{12}^M = (p_{21}^M p_{11}^F + p_{22}^M p_{12}^N)$ . Suppose the state of integrated model changes to (2, 1) at the slot boundary between  $n$  and  $(n + 1)^{\text{th}}$  slots. It actually means that the state of the mobility model changes from fixed to nomadic (from 1 to 2), while the state of teletraffic model remains the same (call is still on). The packet level teletraffic model changes the state from 1 to one, and therefore, one packet is emitted. It is shown by arrow. However, the session completion rate is now  $p_{12}^N = (p_{21}^M p_{12}^F + p_{22}^M p_{12}^N)$  instead of  $p_{12}^F = (p_{11}^M p_{12}^F + p_{12}^M p_{12}^N)$ . In accordance with our assumption  $p_{12}^N > p_{12}^F$ , and therefore, now the session completion is more likely to occur at the next slot boundary compared to previous slot when the mobility model was in fixed state (Fig. 4). Since the state of the packet level teletraffic model changes from 1 to 2, no packets are generated.

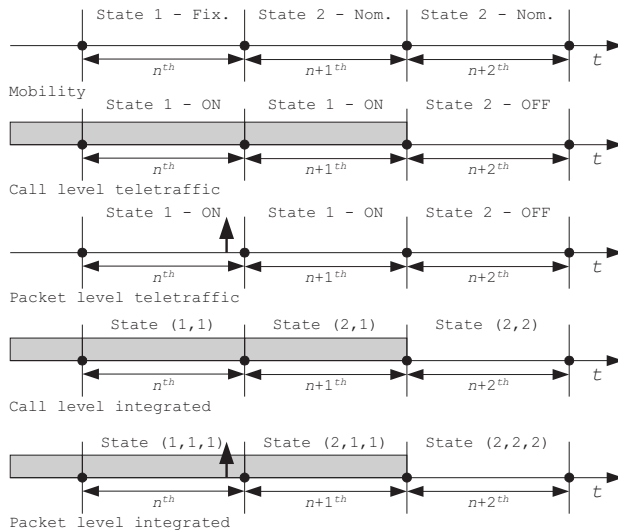


Fig. 4. Microscopic behavior of mobility, call level teletraffic, packet level teletraffic, call level integrated and packet level integrated models.

## VI. EXTENSION TO MULTIPLE APPLICATIONS

It is widely agreed that NG All-IP networks should be designed to support multiple services. In this kind of networks any user is allowed to use different applications at any instant of time. It is well-known that these applications may have different call and packet level characteristics. Therefore, traffic models designed for these networks should integrate models of different traffic sources at both call and packet levels. In what follows an analytical paradigm neces-

sary to add call and packet level models of different applications to already obtained integrated model is proposed. Particularly, we firstly integrate three call level models of different applications into one composite call level model. Then, we associate an appropriate packet level traffic model of applications with corresponding states of call level model.

Taking the same approach as Subsection III-A we assume that when a mobile user is in the fixed state it uses network services with probability  $p^F$ ,  $p^F \in (0, 1)$ , and with probability  $(1 - p^F)$  stays idle. Similarly, when mobile user is on move it accesses services with probability  $p^N$ ,  $p^N \in (0, 1)$ , and does not use the network with complementary probability  $(1 - p^N)$ .

Let us then consider three different applications, namely video, voice and data services. Assume that when the user accesses network services in fixed state it uses video service with probability  $p^F(VID)$ , voice service with probability  $p^F(VCE)$  and data service with probability  $p^F(DAT)$ . Similarly, in nomadic state the user uses video service with probability  $p^N(VID)$ , voice service with probability  $p^N(VCE)$  and data service with probability  $p^N(DAT)$ . To obtain model that takes into account these three different applications it is sufficient to consider a four state Markov chain three of which corresponds to event when call is on with appropriate applications and one state when call is off as shown in Fig. 5.

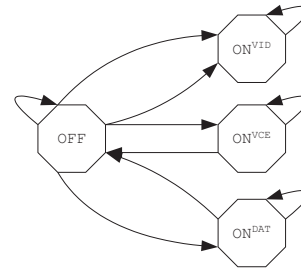


Fig. 5. Call level model of multiple applications.

In accordance with Fig. 5, call level teletraffic model is defined on the following state space:

$$S^C(n) = (OFF, ON^{VID}, ON^{VCE}, ON^{DAT}). \quad (11)$$

where state OFF is common for all applications.

Parameters  $p^F(VID)$ ,  $p^F(VCE)$ ,  $p^F(DAT)$ ,  $p^N(VID)$ ,  $p^N(VCE)$  and  $p^N(DAT)$  depends on user preferences and should be estimated from real measurements of inquiries of users' preferences.

There are two restrictive assumptions of the model presented in Fig. 5. Firstly, it is not possible to generate traffic from two and more applications simultaneously. It is also not allowed to go from one session to another one directly. One may note these two assumption can be relaxed to allow both abovementioned features.

Given the previously defined call level model of multiples applications, one may use an analytical paradigm presented in Section IV to integrate model

of multiple applications into already obtained packet level integrated model.

### VII. ILLUSTRATION OF MODEL'S BEHAVIOR

In this section we give simple examples of user's traffic models. We have to note that our examples do not represent real calling behavior of the user. This is due to the fact that in real environment calling periods are significantly shorter compared to silence periods, and therefore, real models are not convenient for illustrative purposes.

Our first example illustrates the influence of user's mobility behavior on its teletraffic demands. The transition probability matrices of Markov chains representing mobility behavior were chosen as follows:

$$\begin{aligned} P_1^M &= \begin{pmatrix} 0.9 & 0.1 \\ 0.1 & 0.9 \end{pmatrix}, \\ P_2^M &= \begin{pmatrix} 0.9 & 0.1 \\ 0.3 & 0.7 \end{pmatrix}, \\ P_3^M &= \begin{pmatrix} 0.9 & 0.1 \\ 0.6 & 0.4 \end{pmatrix}, \\ P_4^M &= \begin{pmatrix} 0.9 & 0.1 \\ 0.9 & 0.1 \end{pmatrix}. \end{aligned} \quad (12)$$

We choose the following transition probability matrices of the call level model for both fixed and nomadic states are:

$$\begin{aligned} P^F &= \begin{pmatrix} 0.8 & 0.2 \\ 0.3 & 0.7 \end{pmatrix}, \\ P^N &= \begin{pmatrix} 0.5 & 0.5 \\ 0.1 & 0.9 \end{pmatrix}. \end{aligned} \quad (13)$$

We have to note that in order to visually illustrate the influence of mobility on teletraffic demands we chose very high session generation rate in fixed state (13).

Let  $A$  be the event that session is on and let  $I_A$  be its indicator i.e.  $I_A \in \{0, 1\}$ . Obtained traces are shown in Fig. 6 ( $I_A$  versus time). One can notice that with increasing of matrix indices in (12) the mean time the user stays in fixed states increases due to decreasing of the mean time the user spends in nomadic state. With decreasing of mean time spent in nomadic state the overall session generation rate increases. Indeed, the session generation rate in fixed state is three times higher (13). Therefore, in accordance with our model the mobility of the user influence its call level teletraffic demands significantly.

Consider now how the teletraffic demands influence the behavior of call level integrated model. To demonstrate it assume that the mobility of the user and its teletraffic demands in fixed state are restricted to Markov chains governed by the following transition probability matrices:

$$\begin{aligned} P^M &= \begin{pmatrix} 0.8 & 0.2 \\ 0.2 & 0.8 \end{pmatrix}, \\ P^F &= \begin{pmatrix} 0.8 & 0.2 \\ 0.1 & 0.9 \end{pmatrix}, \end{aligned} \quad (14)$$

while the user's teletraffic demands in nomadic state differs according to the following transition probability matrices:

$$\begin{aligned} P_1^N &= \begin{pmatrix} 0.7 & 0.3 \\ 0.1 & 0.9 \end{pmatrix}, \\ P_2^N &= \begin{pmatrix} 0.5 & 0.5 \\ 0.1 & 0.9 \end{pmatrix}, \\ P_3^N &= \begin{pmatrix} 0.3 & 0.7 \\ 0.1 & 0.9 \end{pmatrix}, \\ P_4^N &= \begin{pmatrix} 0.1 & 0.9 \\ 0.1 & 0.9 \end{pmatrix}. \end{aligned} \quad (15)$$

Traces obtained with these parameters are shown in Fig. 7. In accordance with transition probability matrices the mean time user spent in fixed state is equal to mean time spent in nomadic state (14). Therefore, the only difference between models is in the session behavior of the user in these states. The session generation rates in both fixed and nomadic states are the same, while the session duration in nomadic state differs (16). Comparing Fig. 7(a), Fig. 7(b), Fig. 7(c) and Fig. 7(d) one can note that the durations of sessions get smaller. Chi-square test used with level of significance 0.05 have shown that these traces are different.

Consider now a packet level integrated model. Parameter of mobility and call level models were set to:

$$\begin{aligned} P^M &= \begin{pmatrix} 0.6 & 0.4 \\ 0.1 & 0.9 \end{pmatrix}, \\ P^F &= \begin{pmatrix} 0.7 & 0.3 \\ 0.3 & 0.7 \end{pmatrix}, \\ P^N &= \begin{pmatrix} 0.6 & 0.4 \\ 0.1 & 0.9 \end{pmatrix}. \end{aligned} \quad (16)$$

In order to represent a packet arrival process we chose a simple Bernoulli process, which is characterized by single parameter – a probability of one packet arrival. The probability of one packet arrival ( $Pr\{k = 1\}$ ) was set to constant value. Results are shown in Fig. 8(a) and Fig. 8(b) for  $Pr\{k = 1\} = 0.6$  and  $Pr\{k = 1\} = 1.0$  respectively. Boxes denote packet arrivals. One can note that in latter case we have a constant bit rate traffic model.

To illustrate the versatility of the model we then used a Batch Bernoulli Process (BBP) to emulate packet arrivals. Probability function (PF) of the process is shown in Fig. 9(a). Fig. 9(b) shows a trace of the model. This model can be easily extended to include an arbitrary PF of number of generated packets.

### VIII. CONCLUSION

In this paper we presented an integrated model of single packetized VBR traffic source for NG All-IP mobile networks. Our model consists of two parts: mobility model and teletraffic model. The mobility part captures mobility behavior of single user and modelled by Markov chain with finite state space. Teletraffic

part captures teletraffic characteristics at both session and packet levels and represented by superposition of Markov chain and discrete-time batch Markovian arrival process (D-BMAP). Mobility and teletraffic parts are integrated, so that the whole model can be seen as triply stochastic process while does not lead outside the D-BMAP framework.

Our model retain the analytical tractability and can be used in packet-level performance evaluation of NG All-IP networks as well as in simulation studies of these networks. Practically, one can use our model to obtain QoS expectations that particular application may experience at different levels of wireless link congestion. Since proposed model is based on D-BMAP framework it can also be extended to include more general traffic source. The only limiting factor is the state space of the model which should be kept as small as possible.

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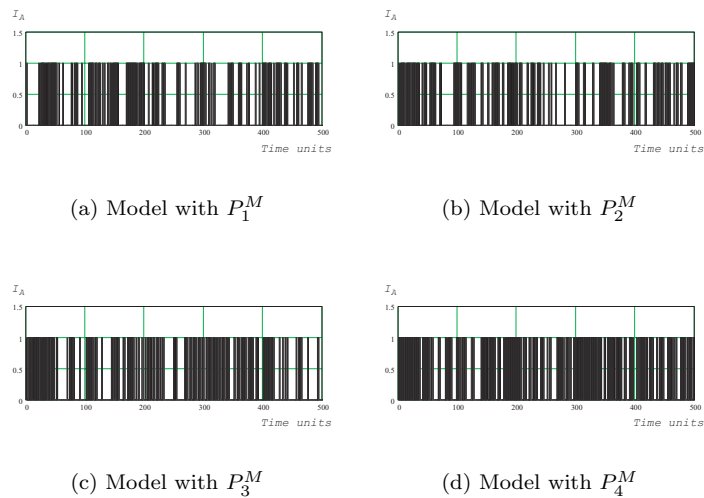


Fig. 6. Modelled traces of integrated call level model with different  $P^M$ .

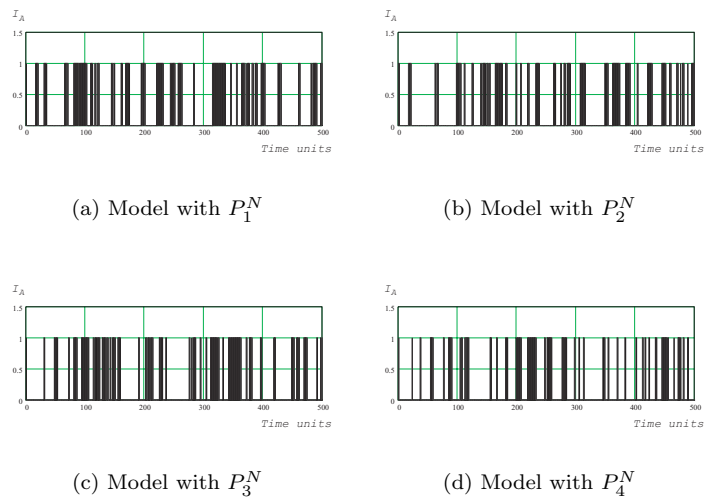


Fig. 7. Modelled traces of the model with different  $P^N$ .

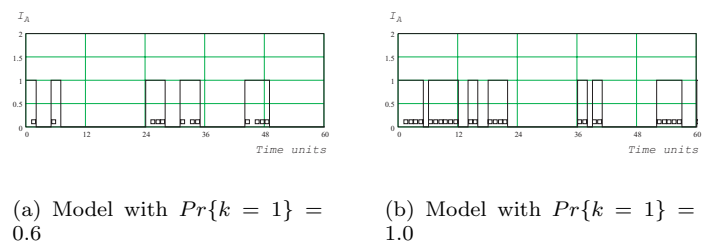


Fig. 8. Traces of packet level integrated model with different  $Pr\{k = 1\}$ .

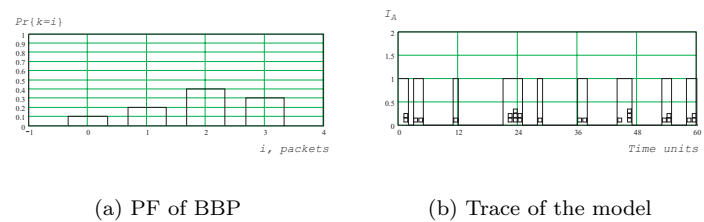


Fig. 9. Packet level integrated model with BPP.