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ERLANG CAPACITY DEGRADATION IN MULTI-ACCESS/MULTI-SERVICE WIRELESS NETWORKS DUE TO TERMINAL/COVERAGE RESTRICTIONS

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ABSTRACT

The benefits of jointly managing the combined radio resources offered by heterogeneous networks consisting of several Radio Access Technologies (RATs) have been profusely studied and assessed in recent years. Nevertheless, most of the existing work assumes scenarios where all RATs are *accessible* (provided the RAT is not at full capacity) to all users demanding service. If this is so, the obtained benefits become rather optimistic given that we neglect the fact that the deployed RATs may have different coverage overlapping conditions among them and that users may not have terminals that support all RATs (i.e. multimode terminals). In this paper we extend a previously developed Markov framework in order to capture the effect of having different coverage overlapping conditions along with the capability of certain terminals to support all or a subset of available RATs. As a result, we assess the degradation, in terms of Erlang capacity, that a heterogeneous network undergoes in scenarios with limited terminal and coverage conditions and compare it to the ideal case of full coverage and full terminal availability.

I. INTRODUCTION

The notion of heterogeneous wireless networks arises in scenarios where multiple Radio Access Technologies (RATs) are deployed in a given area. An operator being responsible of several RATs has the option of managing the combined set of resources in a coordinated way or, on the contrary, to consider each RAT as a separate and independent stand-alone entity. In the first case, Common Radio Resource Management (CRRM) strategies are implemented in order to obtain the utmost and efficient utilization of radio resources while providing the users with some minimum Quality of Service (QoS) [1]. Among the CRRM operations, RAT selection at session/call initiation or during session/call lifetime (a.k.a. vertical handover – VHO) has been the focus of many research papers in the last years (see, e.g. [2] and references therein). The benefits of CRRM over the separate operation (i.e. considering each RAT as an individually-managed entity) have been well addressed and assessed in the literature [3][4]. Nevertheless, to the authors' best knowledge, most of such work assumes that, upon service request, all RATs are potential candidates in the RAT selection procedure. In other words, the considered area is fully covered by all RATs. Moreover, it is commonly assumed that all users are provided with multimode terminals (as opposed to singlemode terminals) thus being able to establish communication through all available RATs. Such assumptions may cause optimistic considerations on the obtained gains through CRRM given they disregard the fact that the deployed RATs may have different coverage overlapping conditions among them and that users may not have terminals that support all RATs. In [5], and related works, Lincke identifies the degradation introduced by the limited operation of singlemode terminals on several traffic overflowing rules among RATs. This work explores the degradation of heterogeneous networks with CRRM for the case of non-ideal coverage and terminal availability conditions. We extend a previously developed Markov framework proposed by the authors in [6] and [7] in order to capture the effect of having different coverage overlapping conditions along with the capability of certain terminals to support all or a subset of available RATs.

The paper is organized as follows. Section II introduces the Markov allocation model that will be conveniently extended in order to capture coverage and terminal capability effects, which are presented in section III. Section IV presents some illustrative results in order to assess the degradation introduced by non-ideal coverage/terminal conditions. Finally, conclusions are given in section V.

II. THE MODEL

In brief (the reader is referred to [6] and [7] for details), the Markovian model definition involves the identification of the state space followed by the definition of the state transition rates and the steady state balance equations.

A. The State Space

A number of J different traffic classes along with K RATs are deployed over a given area. Each RAT supports either all or a subset of the J traffic classes. So as to account for RATs that do not uphold particular traffic classes, a $K \times J$ compatibility matrix, denoted as $\mathbf{B}$, can be defined with elements $b_{kj} = 1$ if RAT k supports traffic type j and $b_{kj} = 0$ otherwise. Based on $\mathbf{B}$, the number of supported services by a given RAT k, J_k, is given by $J_k = \sum_{j=1}^{J} b_{kj}$. Therefore, the Markov state dimension, M, that accounts for the allocation of each supported service into each RAT can be computed as $M = \sum_{k=1}^{K} J_k$.

We may now define the row vector:

$$\mathbf{N}_k = \left[N_{k,1}, N_{k,2}, \ldots, N_{k,l}, \ldots, N_{k,J_k} \right] \in \mathbb{Z}_+^{J_k} \quad (1)$$

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with elements $N_{k,l}$ denoting the number of allocated users in RAT k with supported service l. Note that index l, with $l = 1,2,\ldots,J_k$, corresponds to the l-*th* supported service in RAT k, while j is the available service index.

Taking into account the number of available RATs, the number of allocated users of each supported service in each RAT may be written as a row vector:

$$\mathbf{N} = \left[\ \mathbf{N}_1, \mathbf{N}_2, \ldots,\ \mathbf{N}_k, \ldots, \mathbf{N}_K \right] \in \mathbb{Z}_+^M \tag{2}$$

where $\mathbf{N}$ will be the index to uniquely define each state, hereon denoted as $S_{\mathbf{N}}$, in the Markov chain model.

Assuming that the capacity of a particular RAT k, defined as the maximum allowable number of users of each service type it may handle, is upper-bounded; a finite number of states $S_{\mathbf{N}}$ arises. The limit on the number of states will be set by RAT-specific Call Admission Control (CAC) procedures that determine the maximum number of users this RAT may admit in order to guarantee some minimum QoS requirements. In terms of the number of states, we define the set of feasible states in RAT k, $\mathcal{S}^k$, as:

$$\mathcal{S}^k = \left\{ S_{\mathbf{N}} : 0 \leq f_{\mathbf{N}_k}^k \leq 1 \right\} \tag{3}$$

where $f_{\mathbf{N}_k}^k$ is defined as the *feasibility condition* which accounts for the CAC procedures in RAT k by determining if a given state $S_{\mathbf{N}}$ is feasible in RAT k provided $f_{\mathbf{N}_k}^k$ lays between 0 and 1.

Finally, a given state $S_{\mathbf{N}}$ is said to be feasible if it satisfies $S_{\mathbf{N}} \in \mathcal{S}$ with $\mathcal{S} = \bigcap_{k=1}^{K} \mathcal{S}^k$, i.e. if it is feasible in all RATs.

B. Transition Rates and RAT Selection Policies

Transitions between states $S_{\mathbf{N}} \in \mathcal{S}$ in the resulting M-dimensional Markov chain happen due to service arrival rates, i.e. $\boldsymbol{\lambda} = [\lambda_1, \lambda_2, \ldots, \lambda_j, \ldots \lambda_J]$, or due to service departure rates $\boldsymbol{\mu} = [\mu_1, \mu_2, \ldots, \mu_j, \ldots, \mu_J]$. It is assumed that rates λ_j and μ_j are Poisson and exponentially distributed respectively [8]. Since not all services may be supported by all RATs we define the supported arrival rates into RAT k, $\boldsymbol{\lambda}_k$, as:

$$\boldsymbol{\lambda}_k = \left[\lambda_{k,1}, \lambda_{k,2}, \ldots, \lambda_{k,l}, \ldots, \lambda_{k,J_k} \right] \in \mathbb{R}_+^{J_k} \tag{4}$$

with $\lambda_{k,l}$ the arrival rate of the l-*th* supported service type in RAT k. Note that $\boldsymbol{\lambda}_k$ is a subset of $\boldsymbol{\lambda}$ determined by compatibility matrix $\mathbf{B}$.

A particular traffic allocation policy, referred to as $\pi_{\mathbf{N}}$, is then responsible of determining, at a given state $S_{\mathbf{N}} \in \mathcal{S}$, the specific transition arrival rates of each service type into each of the available RATs, i.e. $\boldsymbol{\lambda}_\pi$, thus:

$$\begin{aligned} \pi_{\mathbf{N}} : \mathbb{R}_+^J &\rightarrow \mathbb{R}_+^M \\ \boldsymbol{\lambda} &\rightarrow \boldsymbol{\lambda}_\pi \end{aligned} \tag{5}$$

where vector $\boldsymbol{\lambda}_\pi$ contains elements $\lambda_{(\pi,k,l)}$ denoting the transition arrival rate of supported service l into RAT k due to policy $\pi_{\mathbf{N}}$ in state $S_{\mathbf{N}}$.

Then, a specific policy π may be implemented by means of a so-called *policy decision function*, $\boldsymbol{\Theta}_{\mathbf{N}} \in \mathbb{R}^M$, with elements $\Theta_{(\mathbf{N},k,l)} \in [0,1]$ (called *policy actions*) determining the fraction of supported traffic l into RAT k in state $S_{\mathbf{N}}$:

$$\lambda_{(\pi,k,l)} = \Theta_{(\mathbf{N},k,l)} \lambda_{k,l} \tag{6}$$

C. Steady State Balance Equations (SSBEs)

In equilibrium, the SSBE for state $S_{\mathbf{N}} \in \mathcal{S}$ results from equalling the inflow rate to the outflow rate in state $S_{\mathbf{N}}$ [8]:

$$\begin{aligned} &P_{\mathbf{N}} \left[\sum_{k=1}^{K} \sum_{l=1}^{J_k} \lambda_{k,l} \Theta_{(\mathbf{N},k,l)} \delta_{(\mathbf{N}+\mathbf{a}_{k,l})} + N_{k,l} \mu_l \delta_{(\mathbf{N}-\mathbf{a}_{k,l})} \right] = \\ &\sum_{k=1}^{K} \sum_{l=1}^{J_k} \lambda_{k,l} \Theta_{(\mathbf{N}-\mathbf{a}_{k,l},k,l)} P_{(\mathbf{N}-\mathbf{a}_{k,l})} \delta_{(\mathbf{N}-\mathbf{a}_{k,l})} + (N_{k,l}+1) \mu_l P_{(\mathbf{N}+\mathbf{a}_{k,l})} \delta_{(\mathbf{N}+\mathbf{a}_{k,l})} \end{aligned} \tag{7}$$

where $P_{\mathbf{N}}$ is the probability of being in state $S_{\mathbf{N}}$, and $\mathbf{a}_{k,l} \in \mathbb{Z}_+^M$ is a row vector containing all zeroes except for the *l-th* supported service in RAT k element which is 1. In addition, $\delta_{\mathbf{N}}$ is an indicator function guaranteeing that non-feasible states are not taken into account, i.e. $\delta_{\mathbf{N}} = 1$ if $S_{\mathbf{N}} \in \mathcal{S}$ and $\delta_{\mathbf{N}} = 0$ otherwise.

Once the SSBEs are determined for all states $S_{\mathbf{N}} \in \mathcal{S}$, numerical methods are applied to solve the resulting system of equations given by the SSBEs plus the normalization constraint $\sum_{S_{\mathbf{N}} \in S} P_{\mathbf{N}} = 1$. The reader is referred to [9] [10] for further details on the numerical solution of Markov chains.

III. RAT Selection with Coverage and Multimode Terminal Availability Constraints

Considering the Markov framework presented in section II, and in the particular case of having 3 RATs, hereon denoted as k_i with $i = \{1,2,3\}$, it is assumed that the RAT selection procedure over a given user u_j requesting service type j in state $S_{\mathbf{N}} \in \mathcal{S}$ prioritizes the RATs according to the ordered set:

$$\mathcal{R}_{\mathbf{N},j}^{\pi} = \left\{ \overline{k}_1, \overline{k}_2, \overline{k}_3 \right\} \tag{8}$$

where, for service j, $\overline{k}_1$ is the RAT with highest priority and $\overline{k}_3$ is the RAT with lowest priority, with $\overline{k}_i \in \{k_1, k_2, k_3\}$ for $i = \{1,2,3\}$.

If p^{t_i} represents the probability that a terminal supports RAT k_i, and p^{a_i} the probability that a user/terminal is covered by RAT k_i during its call/session lifetime; then, the probability that a particular RAT k_i is *eligible* for a given user u_j is the probability, p^{k_i}, that this user has terminal capabilities to support RAT k_i and that this RAT covers such user during its call/session lifetime, i.e.:

$$p^{k_i} = p^{t_i} \cdot p^{a_i} \tag{9}$$

Note that (9) enables to capture in a single parameter, p^{k_i}, the effect of both multimode terminal availability and coverage-related issues which allows us to easily represent and evaluate a great variety of scenarios. In the following subsections, expressions for p^{t_i} and p^{a_i} are derived along with the definition of the policy actions $\Theta_{(\mathbf{N},k,l)}$ taking into account the probability p^{k_i}.

A. Multi-Mode Terminal Availability Model

Assume that the total set of existing terminal types, denoted as $\mathcal{T}$, can be partitioned into $N = 2^K$ mutually exclusive terminal types, denoted by $\mathcal{T}_i$ with $i \in \{0, 2, ..., N-1\}$, such that $\bigcap_{i=0}^{N-1} \mathcal{T}_i = \varnothing$ and $\bigcup_{i=0}^{N-1} \mathcal{T}_i = \mathcal{T}$. Each terminal type $\mathcal{T}_i$ supports a subset of K available RATs. For convenience, we define a $2^K \times K$ matrix $\mathbf{T}$ containing all possible terminal support combinations where elements $t_{(i,k)} = 1$ in $\mathbf{T}$ indicate that terminal type $\mathcal{T}_i$ supports RAT k and $t_{(i,k)} = 0$ otherwise. Each terminal type $\mathcal{T}_i$ is associated with a known probability $\Upsilon_i = \Pr\{\mathcal{T}_i\}$ which can be obtained, e.g., through detailed market studies on the availability of each of the terminal types in a specified location. This probability Υ_i constitutes an input to our model. The probability that a specific user terminal supports RAT k, p^{t_k}, is given by:

$$p^{t_k} = \sum_{i=0}^{N-1} t_{(i,k)} \cdot \Upsilon_i \tag{10}$$

B. Coverage Model

For the coverage model, a similar approach to the multi-mode availability case is adopted. Assume we can partition the whole area of interest $\mathcal{A}$ into $N = 2^K$ mutually exclusive areas denoted by $\mathcal{A}_i$ with $i \in \{0, 2, ..., N-1\}$ such that $\bigcap_{i=0}^{N-1} \mathcal{A}_i = \varnothing$ and $\bigcup_{i=0}^{N-1} \mathcal{A}_i = \mathcal{A}$. Similar to the terminal availability case in section III.A, we define a $2^K \times K$ matrix $\mathbf{A}$ containing all possible coverage overlapping combinations where elements $a_{(i,k)} = 1$ in $\mathbf{A}$ indicate that a user in area $\mathcal{A}_i$ is "covered" by RAT k and $a_{(i,k)} = 0$ otherwise. Each area $\mathcal{A}_i$ is associated to a given known probability $\Psi_i = \Pr\{\mathcal{A}_i\}$, which captures not only the probability that a given user is in a particular area (user location) but also the ability of a given RAT to cover a user (i.e. efficient coverage planning) and that such user is covered during the call/session lifetime (i.e. mobility). As in the previous section, this probability Ψ_i constitutes an input to our model. Then, the probability that a specific user is covered by RAT k during its call/session lifetime, p^{a_k}, is analogous to (10), and can be obtained as:

$$p^{a_k} = \sum_{i=0}^{N-1} a_{(i,k)} \cdot \Psi_i \tag{11}$$

C. RAT Selection Formulation

Under the assumption that RAT selection policy π at a given state $S_{\mathbf{N}} \in \mathcal{S}$ prioritizes the RATs according to the set $\mathcal{R}_{\mathbf{N},j}^{\pi}$ in (8), we intend to determine the fraction of supported traffic l into each RAT k, $\lambda_{(\pi,k,l)}$ as in (6). For ease of representation, let the Boolean C_{l,k_i} indicate that resources for service l in RAT k_i are available and $\overline{C}_{l,k_i}$ otherwise. Then, for the case of the RAT with highest priority $\overline{k}_1$ we have

$$\lambda_{(\pi,\overline{k}_1,l)} = \left\{ \begin{array}{ll} \lambda_{\overline{k}_1,l} \cdot p^{\overline{k}_1} & \text{if } C_{l,\overline{k}_1} \\ 0 & \text{otherwise} \end{array} \right\} = \Theta_{(\mathbf{N},\overline{k}_1,l)} \cdot \lambda_{\overline{k}_1,l} \tag{12}$$

Expression (12) states that service l will be allocated to $\overline{k}_1$ (which is the preferred option) provided $\overline{k}_1$ has enough capacity to admit this user and that $\overline{k}_1$ is eligible (i.e. terminal supports RAT $\overline{k}_1$ and it is covered by RAT $\overline{k}_1$ along the call/session lifetime).

For the case of the second "preferred" RAT, the fraction of traffic l into $\overline{k}_2$ yields:

$$\lambda_{(\pi,\overline{k}_2,l)} = \left\{ \begin{array}{ll} \lambda_{\overline{k}_2,l} \cdot (1 - p^{\overline{k}_1}) \cdot p^{\overline{k}_2} & \text{if } C_{l,\overline{k}_1} \wedge C_{l,\overline{k}_2} \\ \lambda_{\overline{k}_2,l} \cdot p^{\overline{k}_2} & \text{if } \overline{C}_{l,\overline{k}_1} \wedge C_{l,\overline{k}_2} \\ 0 & \text{otherwise} \end{array} \right\} = \Theta_{(\mathbf{N},\overline{k}_2,l)} \cdot \lambda_{\overline{k}_2,l} \tag{13}$$

And the third "preferred" RAT, the fraction of traffic l into $\overline{k}_3$ yields:

$$\lambda_{(\pi,\overline{k}_3,l)} = \left\{ \begin{array}{ll} \lambda_{\overline{k}_3,l} \cdot (1 - p^{\overline{k}_1}) \cdot (1 - p^{\overline{k}_2}) \cdot p^{\overline{k}_3} & \text{if } C_{l,\overline{k}_1} \wedge C_{l,\overline{k}_2} \wedge C_{l,\overline{k}_3} \\ \lambda_{\overline{k}_3,l} \cdot (1 - p^{\overline{k}_2}) \cdot p^{\overline{k}_3} & \text{if } \overline{C}_{l,\overline{k}_1} \wedge C_{l,\overline{k}_2} \wedge C_{l,\overline{k}_3} \\ \lambda_{\overline{k}_3,l} \cdot (1 - p^{\overline{k}_1}) \cdot p^{\overline{k}_3} & \text{if } C_{l,\overline{k}_1} \wedge \overline{C}_{l,\overline{k}_2} \wedge C_{l,\overline{k}_3} \\ \lambda_{\overline{k}_3,l} \cdot p^{\overline{k}_3} & \text{if } \overline{C}_{l,\overline{k}_1} \wedge \overline{C}_{l,\overline{k}_2} \wedge C_{l,\overline{k}_3} \\ 0 & \text{otherwise} \end{array} \right\}$$
$$= \Theta_{(\mathbf{N},\overline{k}_3,l)} \cdot \lambda_{\overline{k}_3,l} \tag{14}$$

IV. Numerical Results

A. Settings and Performance Metrics

We assume $K = 3$ RATs, k_1, k_2 and k_3, and $J = 2$ services, j_1 and j_2. Moreover, it is considered that service j_1 is supported only by RATs k_1 and k_2 and that service j_2 is supported only by RATs k_2 and k_3. According to this, the resulting compatibility matrix, $\mathbf{B}$, is:

$$\mathbf{B} = \begin{pmatrix} 1\,0 \\ 1\,1 \\ 0\,1 \end{pmatrix} \quad (15)$$

from which a $M = 4$ -dimensional Markov model arises. As in [4], and for the sake of brevity, linear feasibility conditions, $f_{\mathbf{N}_k}^{k}$, are considered:

$$f_{\mathbf{N}_{k_1}}^{k_1} = \frac{N_{k_1,j_1}}{A_{k_1,j_1}},\ f_{\mathbf{N}_{k_2}}^{k_2} = \frac{N_{k_2,j_1}}{A_{k_2,j_1}} + \frac{N_{k_2,j_2}}{A_{k_2,j_2}},\ f_{\mathbf{N}_{k_3}}^{k_3} = \frac{N_{k_3,j_2}}{A_{k_3,j_2}} \quad (16)$$

where practical values of $A_{k_1,j_1} = 5$, $\left(A_{k_2,j_1}, A_{k_2,j_2}\right) = \left(6,4\right)$ and $A_{k_3,j_2} = 4$ have been considered, representing the maximum number of users of each service type into each RAT. The RAT selection policy is such that for service j_1 the system chooses the RAT according to the following precedence: $\mathcal{R}_{\mathrm{N},j_1}^{\pi} = \{k_1,k_2\}$; while as for service j_2 the priority is $\mathcal{R}_{\mathrm{N},j_2}^{\pi} = \{k_3,k_2\}$ (recall that k_1 does not support service j_2 and k_3 does not support service j_1).

As for the performance metric we use the *Erlang Capacity* [4], defined as the set of offered traffic of each service, i.e. $T_{j_1} = \lambda_{j_1}/\mu_{j_1}$ and $T_{j_2} = \lambda_{j_2}/\mu_{j_2}$, provided some QoS requirement is met. In this paper, we assume QoS requirements are in terms of per-service blocking probability ($P_{b,j}$). Thus the Erlang capacity for RAT k (E_k) may be expressed as:

$$E_k = \left\{\left(T_{j_1}, T_{j_2}\right): P_{b,j_1} \le P_{b,j_1}^{*}, P_{b,j_2} \le P_{b,j_2}^{*}\right\} \quad (17)$$

where P_{b,j_1}^{*} and P_{b,j_2}^{*} are the maximum blocking probabilities which are set to be $P_{b,j_1}^{*} = P_{b,j_2}^{*} = 0.02$. Then, E_k reflects the maximum values of $\left(T_{j_1}, T_{j_2}\right)$ that fulfil the abovementioned QoS requirements.

In our multi-access system, the average served j traffic in RAT k can be computed from the steady state probabilities, $P_{\mathbf{N}}$, as:

$$N_{(j,k)} = \sum_{S_{\mathbf{N}} \in S} (\mathbf{e}_{k,j} \cdot \mathbf{N}^T) \cdot P_{\mathbf{N}} \quad (18)$$

with $\mathbf{e}_{k,j}$ a row-vector containing all zeroes except for the j-*th* service in RAT k (if supported) which is 1. The per-service carried traffic is the sum of traffics over all RATs, i.e.:

$$N_j = \sum_{k=1}^{K} N_{(j,k)} \quad (19)$$

In addition, carried traffic can be alternatively computed as:

$$N_j = T_j \cdot \left(1 - P_{b,j}\right) \quad (20)$$

Thus, the blocking probability can be expressed as:

$$P_{b,j} = 1 - N_j / T_j \quad (21)$$

Note that the blocking probability will not only take into account the denial of service due to the unavailability of free resources but also, if such is the case, the lack of terminal capabilities and/or favourable coverage conditions determined by the probability p^{k_i} given in (9).

B. *Performance Evaluation*

Figure 1 shows the Erlang capacity limits (i.e. the maximum offered traffic of each service that fulfils QoS requirements) for the case of full coverage and full multi-mode terminal availability (in blue, hereon referred to as ideal case); and for the case that we have constraints in terms of coverage and/or multi-mode terminal availability (in red, hereon referred to as restricted case). For the restricted case we assume the following values for probabilities p^{k_i} in (9): $(p^{k_1}, p^{k_2}, p^{k_3}) = (1, 0.95, 0.9)$. For the sake of comparison, we also include the resulting Erlang capacity when no coordination among RATs is available (in green, hereon denoted as No-CRRM case). The Erlang capacity for the No-CRRM case is obtained from the sum of Erlang capacities of the different RATs regarded as individual entities as in [4]. In this sense, the Erlang capacities for the different RATs are also plotted in Figure 1. Note that for RATs k_1 and k_3, the Erlang capacity region is a line over the abscissa and ordinate respectively, given that RAT k_1 does not support service j_2 and RAT k_3 does not support service j_1. It is clear from Figure 1 that both the ideal and the restricted cases outperform the No-CRRM case, which is, on the other hand, somewhat expected and assessed. Nevertheless, a noticeable degradation in the restricted case with respect to the ideal case can be observed. This follows from higher blocking probabilities in the restricted case due to terminal/coverage limitations than in the ideal case where blocking is only due to resource unavailability.

In order to quantify the degradation level introduced by the restricted case, we compute, for both the ideal and the restricted case, the Erlang capacity gain over the No-CRRM case as a function of the traffic service mix ($\gamma \in \left[0,1\right]$) given by:

$$\gamma = T_{j_1} / (T_{j_1} + T_{j_2}) \quad (22)$$

where we have plotted T_{j_2} as a function of T_{j_1} for different values of γ in Figure 1 resulting in the dashed lines crossing the origin of coordinates. The intersection of such lines with the Erlang capacity curves (marked with circles) corresponds to the maximum Erlang capacity for a specific γ. The resulting Erlang capacity gains of the ideal and restricted cases over the No-CRRM case are plotted in Figure 2 for the complete range of values of γ. We notice that while for the ideal case up to 80% gains can be achieved over the No-CRRM case (see at $\gamma \approx 0.65$), the impact of limited conditions on terminal support and coverage reduces this maximum gain to just below 60% (see at $\gamma \approx 0.6$). As for the minimum gain, in the ideal case we achieve over 40% gain whereas for the restricted case the minimum gain drops to below 20%, i.e. a degradation of 50% with respect to the ideal case. It is worthwhile noticing that the behaviour of curves with respect to γ in Figure 2 corresponds to the particular RAT selection policy and the considered feasibility regions for this study case. Other RAT selection criteria may lead to different behaviour of such Erlang capacity gains as a function of the offered service mix. This was already pointed out in [4], where service-based assignment gains, such as in our case, are significantly sensitive to the offered service mix. Since we are interested in determining the degradation introduced by limited conditions in terms of coverage and/or terminal support, results in Figure 2 quantify such degradation while we leave the impact of RAT selection for further work.

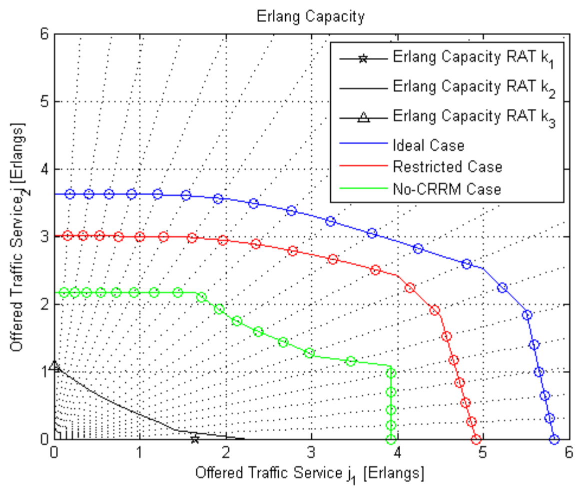

Figure 1: Erlang capacity for the considered study cases.

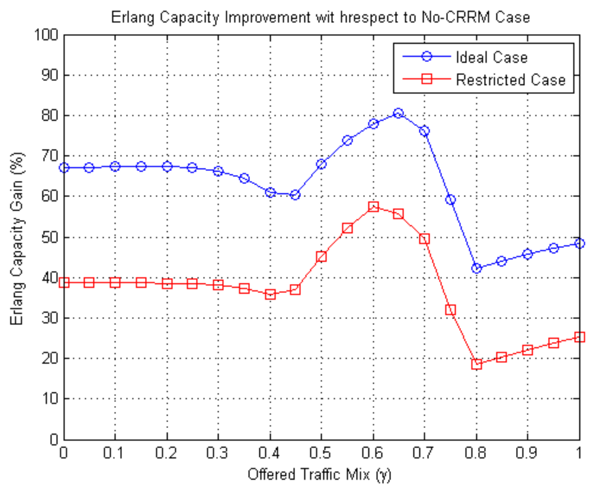

Figure 2: Erlang Capacity gain of CRRM over No-CRRM for the ideal and the restricted case.

V. CONCLUSIONS

In this work we have extended a previously developed Markov framework for the allocation of multi-service users in multi-access networks. In order to capture the access restrictions imposed by users with terminal capability limitations along with different levels of coverage overlapping among RATs, we introduce a statistical parameter that accounts for such scenarios. In our simple but yet practical case study, results indicate that, although high gains can be achieved from CRRM over a separate operation among RATs (which is, on the other hand, widely acknowledged), this potential gain is severely degraded due to non-ideal situations imposed by limitations in terms of terminal multimode operation and coverage issues. Future work will determine the impact of RAT selection strategies on such degradation.

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