Traffic from Mobility in Mobile Broadband Systems

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Models allowing the study of the influence of coverage distance and velocity on the supported traffic and on the new calls traffic linear density are examined, and results are obtained for typical scenarios in a Mobile Broadband System (MBS) with a linear coverage geometry. For systems without guard channels for handover, for a fixed bounding value for the blocking probability, the new calls traffic linear density was analyzed, increasing with the decrease of the maximum coverage distance, *R*, being upper limited by a value which depends on the characteristics of the mobility scenario. However, call-dropping probability requirements also need to be fulfilled, leading to a new calls traffic density that only increases with the decrease of *R* down to an optimum value of *R*, and being lower for scenarios with higher mobility. These optimum values of *R* are higher for scenarios with higher and higher mobility, leading to limitations in system capacity, mainly for high mobility scenarios. In order to resolve these limitations, the use of guard channels for handover is studied, particularly for high mobility scenarios. For these scenarios one concludes that there is a degradation in system capacity because, for the typical coverage distances foreseen for MBS, the new calls traffic linear density is one order of magnitude below the values obtained for the pedestrian scenario (where it is approximately 15 Erlang/km), decreasing from 2.47 Erlang/km, in the urban scenario, down to 0.84 Erlang/km, in the highway scenario, when two guard channels are used.

1 Introduction

Mobile Broadband Systems will allow extending high data rates provided by the fixed broadband-ISDN to the cellular communications market, supporting high speed communications in high mobility outdoor scenarios [1], leading to the use of millimetre wavebands. For such bands, shadowing from buildings is important, the propagation being mainly in line-of-sight. As a consequence, for urban scenarios the system will be based on a microcellular structure with cells confined to streets, having dimensions in the order of a few hundred metres [2]; also for main road scenarios, the use of microcells is foreseen.

The high mobility associated with the future Mobile Broadband System (MBS) yields a teletraffic analysis where both the new calls and the handover traffic should be considered simultaneously. For systems where guard channels for handover are used, this analysis is made assuming that handover traffic is Poisson distributed [3], and that there is independence among the number of calls being served at each cell [4].

One of the goals of system planning is the maximization of the new calls traffic in terms of the cells dimension, i.e. one is interested in obtaining the cell coverage range that leads to a maximum new calls traffic density supported by the system. For the case of linear geometry, where mobiles travel randomly through cells with maximum coverage length R, total length $L = 2R$, and base stations located in the centre, located end-to-end (Figure 1), a new calls traffic per unit length ξ_n (or new calls traffic linear density) is considered. To have an insight into the trade-offs involved in the optimization procedure for MBS, the behaviour of ξ_n in terms of the maximum coverage distance of a cell R, needs to be studied for typical values of R, and for various mobility scenarios: static, pedestrian, urban, main roads and highways.

At first glance, one could consider that the new calls traffic linear density should be proportional to $(1/R)$; however, this is only valid for the static scenario, where there are no handovers. In scenarios with mobility, the number of calls generated by handover increases as L decreases and the velocity increases, implying that ξ_n does not increase linearly with $(1/R)$. For a given supported traffic, the increasing behaviour of ξ_n, associated with the decrease of the coverage distance, corresponds to an increase of the cross-over rate η (number of handovers per unit length) [4]. These facts originate higher probabilities for handover failure P_{hf} and call dropping probabilities P_d with the decrease of R.

The simple situation of homogeneous traffic (constant value of new calls traffic in the whole service area) and linear coverage geometry (where mobiles handover between the first and the last cells, a typical geometry for roundabouts [5]) will be considered here as a first step to a more complicated (and closer to reality) analysis. The objective of the design is to obtain values for R that verify the requirements of system quality. These requirements consist of values lower than 1 – 2 % for the blocking probability P_b [6] and lower than 0.1 – 0.5 % for the call dropping probability [7].

When no guard channels for handover are used the blocking and the handover failure probabilities are equal, which strongly limits system capacity for high handover failure probabilities, i.e. low coverage distances. If guard channels for handover are used, equations for blocking and handover failure probabilities will be decoupled, and trade-offs can be used to improve system performance in the case of small cells.

Although MBS will be a multi-service system, providing multimedia mobile communications handling both bursty and constant bit-rate traffic, in this work only a single service will be taken into account in order to simplify this first analysis of the problem. A service with mean duration of 3 min is considered as an example. Anyway, this analysis will be very useful in the computation of multi-service aggregated traffic, because the first step of this more general problem [8] consists of computing, for each type of traffic, the state probability as if it was the only kind of traffic in the system.

In Section 2, the influence of traffic from mobility on the microcellular coverage distance is examined. Time parameters are described and the handover probability is introduced. The characteristics of some main mobility scenarios are introduced and formulas for the cross-over rate are then obtained, from which values for the average cross-over velocity are calculated. In systems without guard channels for handover, for given values of the number of channels in each cell and of P_b, one can calculate the corresponding supported traffic. Equations for the new calls traffic and the traffic coming from handover are also obtained.

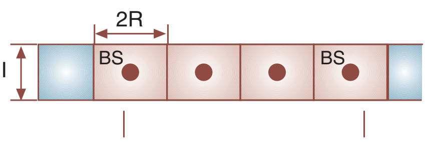

Figure 1 Linear coverage geometry

Models for the computation of new calls traffic linear density are presented, its dependence on R is highlighted and the resulting limitations in system capacity imposed because of the high mobility of terminals are discussed.

In Section 3, the use of guard channels for handover is proposed as a prospective solution to overtake the limitations discussed in Section 3 for the new calls traffic linear density. First, the assumptions made in the traffic analysis are described. Finally, the trade-offs involved in the design are described and results are obtained for the supported traffic, the new calls traffic linear density and coverage distances that maximize it.

Finally, in Section 4, some conclusions are drawn on the influence of mobility on the new calls traffic linear density and its consequences on the optimization of MBS capacity.

2 Influence on the Optimum Microcellular Coverage Distance

2.1 Traffic Requirements

In a linear coverage geometry, cells are placed end-to-end and mobiles can handover from a cell only to one of the two adjacent ones, Figure 2; a call comprises successive sessions τ_1, τ_2, τ_3, ... in cells traversed by a mobile terminal, and its duration τ follows an exponential distribution whose mean is $\bar{\tau} = 1 / \mu$ [4], where μ is the service rate. The channel occupancy time τ_c is the time spent by a user in communication prior to handover (or subsequent to handover) or call completion, which can also be modelled by an exponential distribution with reasonable accuracy [9].

The cell dwell time τ_h is the residing time of a mobile within a cell. Further assuming that the dwell time is exponentially distributed with mean $\bar{\tau}_h = 1 / \eta$, then the channel occupancy time is $\tau_c = \min\{\tau, \tau_h\}$, i.e. it is either the time spent in a cell before crossing the cell boundary if the call continues, or the time until the channel is relinquished [4]. As the minimum of two exponentially distributed random variables is also exponentially distributed with parameter $\mu_c = \mu + \eta$, the mean channel occupancy time is given by

$$\bar{\tau}_c = \frac{1}{\mu_c} = \frac{1}{\mu + \eta} \tag{2.1}$$

the probability of handover being given by

$$P_h = \text{Prob}\{\tau > \tau_h\} = \frac{\eta}{\mu + \eta} = \frac{\bar{\tau}_c}{\bar{\tau}_h} \tag{2.2}$$

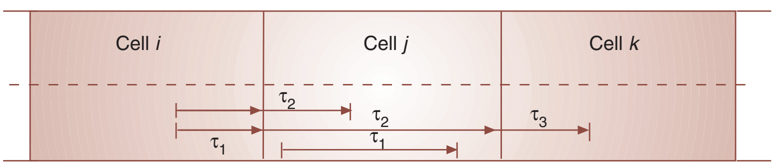

Figure 2 Dwell time and channel occupancy time

Usually the service rate is assumed to be known for the service or application under analysis, and the cross-over rate can be calculated taking into account the distribution for velocities [3]

$$\eta = \frac{1}{\int_0^{V_{max}} \left(\frac{2R}{v}\right) \cdot f(v) dv} \tag{2.3}$$

where v is the velocity and f is the velocity probability density function (note that in a linear geometry the total length of the cells is $2R$).

For a properly designed system, the new calls traffic density increases as the coverage distance decreases, owing to the increase of the handover rate (mean number of handovers per call when the probability of the handover failure is negligible) [4]; this also causes the increase of handover failure and call dropping probabilities. The desired maximization of the new calls traffic linear density obeys to requirements of system quality, which consist of values lower than 1 – 2 % [6] for the blocking probability and lower than 0.1 – 0.5% for the call dropping probability [7]. An improvement in system performance can be achieved if guard channels are used for handover, but different solutions are obtained depending on mobility scenarios and on the number of guard channels for handover, g: a total number of channels $m = g + c$ is considered, where c is the number of channels to support both new and handover calls (Figure 3).

The call dropping probability P_d is given by [4]

$$P_d = P_h P_{hf} \sum_{i=0}^{\infty} P_h^i (1 - P_{hf})^i \tag{2.4}$$

where i denotes the order of the handover and P_{hf} is the handover failure probability. For small values of P_{hf}, it can be approximated by

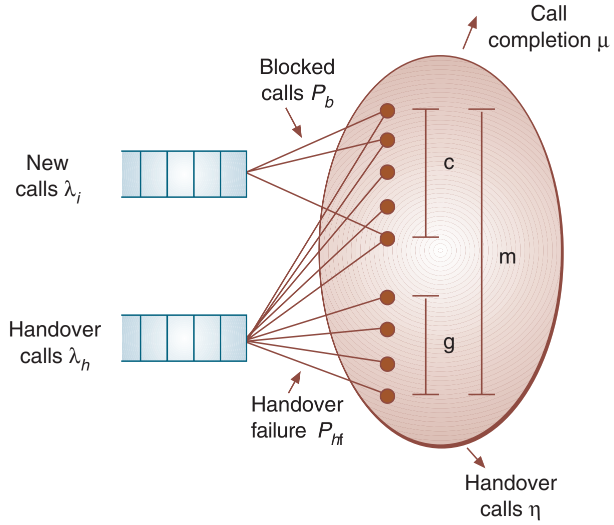

Figure 3 Model for the traffic in the case where the use of guard channels for handover is considered (extracted from [3])

$$P_d = \frac{\eta}{\mu} \cdot P_{hf} = \zeta \cdot P_{hf} \tag{2.5}$$

where ζ is the handover rate.

If guard channels for handover were not used, P_{hf} would be equal to the blocking probability P_b [10], which imposes a strong limitation because P_b would be as low as P_d determines. The use of guard channels for handover allows overtaking this limitation because P_b and P_{hf} will be decoupled [10]. In this case, depending on the coverage distance, the design is made by considering the traffic supported by m channels, from which g are guard channels [4].

The parameters involved in the design depend on the call generation rate λ, the number of channels at each cell m, besides v and μ. The simple situation of homogeneous traffic (constant value of new calls traffic in the whole service area) and linear coverage geometry (where mobiles handover between the first and the last cells, typical for circular geometry [5]) will be considered here as a first step to a more complicated (and closer to reality) analysis.

2.2 Mobility Scenarios

The scenarios examined in the analysis are presented in Table 1, where a triangular distribution, with average $V_{av} = (V_{\max} + V_{\min}) / 2$ and deviation $\Delta = (V_{\max} - V_{\min}) / 2$, is considered for the velocity [3] (Figure 4).

The probability density function is given by

$$f(v) = \begin{cases} \frac{1}{\Delta^2} \cdot [v - (V_{av} - \Delta)], & V_{av} - \Delta \le v \le V_{av} \\ -\frac{1}{\Delta^2} \cdot [v - (V_{av} + \Delta)], & V_{av} \le v \le V_{av} + \Delta \\ 0, & \text{otherwise} \end{cases} \tag{2.6}$$

which leads, when $V_{\min}, \Delta > 0$, to the following cross-over rate

$$\eta = \left\{ \frac{2R}{\Delta^2} \left[(V_{av} + \Delta) \cdot \ln\left(\frac{V_{av} + \Delta}{V_{av}}\right) - (V_{av} - \Delta) \cdot \ln\left(\frac{V_{av}}{V_{av} - \Delta}\right) \right] \right\}^{-1} \tag{2.7}$$

and when $V_{\min} = 0$ ($\Delta = V_{av}$), to the limit

$$\eta = \frac{V_{av}}{2 \cdot \ln(2)} \cdot \frac{1}{(2R)}. \tag{2.8}$$

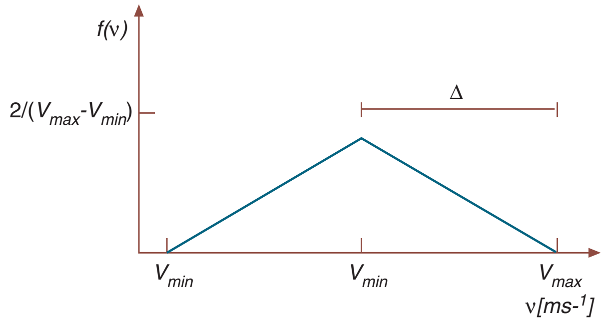

Figure 4 Velocity probability density function

Defining the average cross-over velocity η^* as

$$\eta^* = \eta \cdot (2R) \tag{2.9}$$

(η normalized to the cell length $2R$) one obtains, for the scenarios from Table 1, the values of Table 2.

The interest in defining this parameter is that it enables us to make explicit the dependence on R of some parameters to be defined later.

2.3 New Calls Traffic Linear Density without Guard Channels for Handover

For given values of m and P_b and a configuration which does not use guard channels for the handover calls, one can calculate the corresponding traffic $\rho_m = \lambda / \mu$ by using the well known Erlang-B model [13]. The new calls traffic, ρ_n, and the traffic coming from handover, ρ_h, can then be obtained as [3]

$$\rho_n = \frac{\mu}{\eta + \mu} \cdot \rho_m = \frac{2\mu R}{\eta * + 2\mu R} \cdot \rho_m \tag{2.10}$$

$$\rho_h = \frac{\eta}{\eta + \mu} \cdot \rho_m = \frac{\eta *}{\eta * + 2\mu R} \cdot \rho_m \tag{2.11}$$

where the dependence on the cell length has been made explicit by introducing the cross-over average velocity. Note that $\rho_m = \rho_n + \rho_h$.

Dividing (2.10) by ($2R$) one obtains a new calls traffic linear density

Table 1 Scenarios of mobility characteristics

Scenario	$V_{av}[m \cdot s^{-1}]$	$\Delta\ [m \cdot s^{-1}]$
Static	0	0
Pedestrian	1	1
Urban	10	10
Main roads	15	15
Highways	22.5	12.5

Table 2 Average cross-over velocity

Scenario	$\eta^*[m \cdot s^{-1}]$
Pedestrian	0.72
Urban	7.21
Main roads	10.82
Highways	21.21

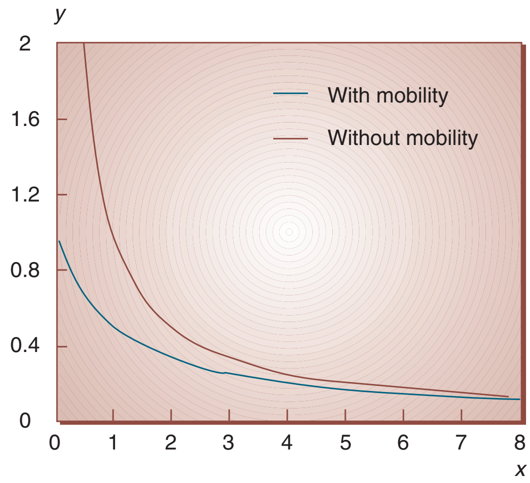

Figure 5 Normalized new calls linear traffic density y as a function of x

$$\xi_n = \frac{\rho_n}{2R} = \frac{\mu}{(\eta * +2\mu R)} \cdot \rho_m \tag{2.12}$$

which can be normalized as follows

$$y = \frac{\xi_n}{\rho_m \cdot \mu / \eta *} = \frac{1}{1 + (\mu(2R)/\eta *)} = \frac{1}{1+x} \tag{2.13}$$

where $x = \mu(2R) / \eta^*$.

For the static scenario the new calls traffic linear density is $\xi_n = \rho_m / (2R)$ because $v = 0$ and $\eta^* = 0$. Consequently, in a non-static scenario, if the contribution of mobility was not considered, one would obtain $y = 1/x$.

From the operator's point of view the objective is to maximize ξ_n, thus the dependence of this parameter on R should be analyzed. Given constant values of the blocking probability, one obtains the graphs from Figure 5 for both situations (with and without mobility).

Then, one could conclude that ξ_n is upper limited by $(\rho_m \mu / \eta^*)$ [/m], which decreases with velocity. However, one should note that for a given R, x will be lower for higher velocities, and so y will be larger, which partly compensates for the lower values of $(\rho_m \mu / \eta^*)$ in equation (2.12).

However, call dropping probability restrictions also need to be fulfilled. Because $P_b = P_{hf}$, the blocking probability should be computed according to (2.5) [3] and, because of that, the blocking probability will be a linear function of R with slope $2\mu(P_d)_{max} / \eta^*$.

So, the traffic supported by m channels will depend on R. For the considered scenarios an example is given in Figure 6 where: $m = 11$, $P_d = 0.5$ %, $\mu = 1/3$ min^{-1}, and the values for the average velocity V_{av} and the velocity deviation Δ are the ones presented in Table 1.

As can be seen, the supported traffic will not be constant, rather having a decreasing behaviour with the decrease of R. In this case, the dependence of ξ_n on R will be as presented in Figure 6b) for the three scenarios with higher mobility, i.e. for each scenario, there is an optimum value for the coverage distance which maximizes ξ_n. These maxima correspond to lower values of R for the scenarios with lower mobility, being lower for the scenarios with higher mobility. For coverage distances lower than this optimum value, ξ_n decreases with the decrease of R. This is due to call dropping probability restrictions, which contradicts the behaviour expected with the simple analysis without considering it. It is also worth noting that the new calls traffic linear density is much more sensitive to the mobility scenario than the supported traffic because the former, besides the dependence on ρ_m, also depends on P_h.

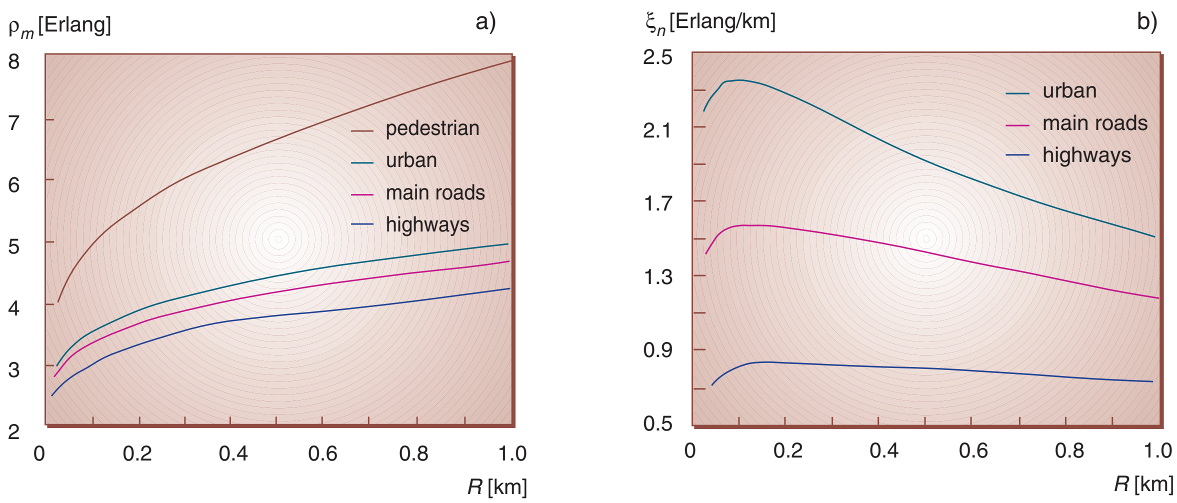

Figure 6 Traffic for m = 11 channels and the design made according to the call dropping probability restrictions a) Traffic supported, b) New calls traffic linear density

3 Traffic from Mobility with Guard Channels for Handover

3.1 Blocking and Handover Failure Probabilities

Considering the use of guard channels for handovers when no queueing of new or handover calls is performed, the blocking and handover failure probabilities are given by [3]. This is assuming that the handover traffic can be approximated by a Poisson process [8] and that the new calls traffic is also Poisson distributed, which is valid for a number of users in a cell much larger than the supported traffic.

$$P_b = \frac{(\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h^k}{k!}}{\sum_{k=0}^{c-1} \frac{(\rho_n+\rho_h)^k}{k!} + (\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h^k}{k!}} \quad (3.1)$$

$$P_{hf} = \frac{(\rho_n + \rho_h)^c \frac{\rho_h^g}{(c+g)!}}{\sum_{k=0}^{c-1} \frac{(\rho_n+\rho_h)^k}{k!} + (\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h^k}{k!}} \quad (3.2)$$

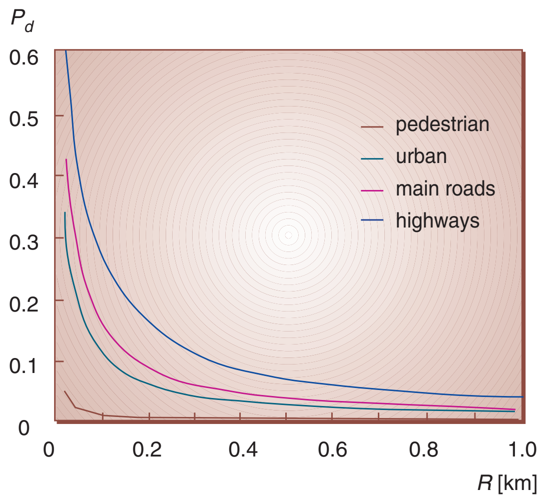

Figure 7 Call-dropping probability for g = 0

where ρ_n is the new calls traffic and ρ_h is the handover traffic. The traffic supported by m channels is then $\rho_{m,g} = \rho_n + \rho_h$.

The new calls traffic and the traffic coming from handover can then be easily obtained as in Section 3.3, replacing ρ_m by $\rho_{m,g}$ [3]. The new calls traffic linear density is then given by

$$\xi_n = \frac{\rho_n}{2R} = \frac{1}{1 + 2\mu R/\eta*} \cdot \frac{\mu}{\eta*}\rho_{m,g} \quad (3.3)$$

For a fixed $\rho_{m,g}$ and a given μ, ξ_n is upper bounded by $\mu / \eta*$, decreasing with the increase of the cross-over velocity, and having a variation with R of the type $1 / (1 + x)$, where x is directly proportional to R and inversely proportional to the cross-over average velocity.

3.2 Supported Traffic

The examples given here were obtained for the conditions mentioned before. For $g = 0$, using the supported traffic $\rho_{m,g}$ that verifies $P_b = 2$ %, which does not depend on R, one obtains values for the new calls traffic linear density that increase with the decrease of the coverage distance. However, the corresponding call-dropping probability constraints associated with (2.5) and with P_b being equal to P_{hf} (Figure 7) are only fulfilled in the pedestrian scenario and only for $R > 300$ m. A way to resolve this limitation without drastically decreasing the new calls traffic linear density, is the use of guard channels for handover.

From an operator's point of view, in order to achieve MBS provisional coverage distances, approximately in the range 100 – 350 m [2], one intends to increase ξ_n while R decreases. In order to obtain results for the supported traffic the procedure was the following: taking $P_d = 0.5$ %, (2.5) was used to get a value for P_{hf}. With this P_{hf} value and with $P_b = 2$ %, (3.1) and (3.2) were solved separately for the supported traffic $\rho_{m,g}$ (using (2.10) and (2.11)), and the respective values, ρ_{Pb} and ρ_{Phf}, were obtained. In order to cope with both probability requirements, the minimum of these two must be taken.

While $\rho_{Pb}(R)$ is almost constant with R (the right part of the curves in Figure 8 (example for $g = 1$)), $\rho_{Phf}(R)$ increases with R (since it was obtained according to (2.5) and η depends on R, as in (2.8) and (2.9)) (the left part of the curves). Thus, a breakpoint exists at the intersection of both curves, where $\rho_{Phf}(R) = \rho_{Pb}(R)$, and for values of R lower than this breakpoint the curves have then an appreciable slope. One can observe that the supported traffic decreases as the velocity of the associated scenario increases, mainly in the zone of the curves limited by handover failure. It can also be seen that the breakpoint occurs for increasing values of R for faster and faster mobiles.

As could be expected, when g increases, $\rho_{Pb}(R)$ decreases. However, as $\rho_{m,g}(R)$ is the minimum between $\rho_{Pb}(R)$ and $\rho_{Phf}(R)$, this decrease is only effective for the part of the curves where $\rho_{Pb}(R)$ is lower than $\rho_{Phf}(R)$. The challenge in the design for low values of R is finding values for g that, for a given m, both maximize ρ_{Phf} and keep it lower than ρ_{Pb}, mainly for the scenarios with high mobility (urban, main roads and highways).

3.3 New Calls Traffic Linear Density

For given values of m and g, we can then obtain the curves for the new calls traffic linear density $\xi_n(R)$ according to (3.3). Figures 9 and 10 show these curves for $g = 1, 2$ (the latter only for the higher mobility scenarios). For the pedestrian case, as $\rho_{m,g}$ is almost constant for all the range of R, we basically observe that it follows the behaviour of the ratio at the right member from (2.3). For the three scenarios with higher mobility, $\xi_n(R)$ presents maxima, depending on the velocity and on g. These maxima occur for distances lower than the breakpoints, for design purposes corresponding to optimum values of R, R_{opt} (Table 3), and agreeing with the provisional values for MBS and also with the need to use larger cell lengths for high mobility scenarios owing to the cost associated with signalling [12]. One can also see that the breakpoints occur for lower coverage distances as g increases.

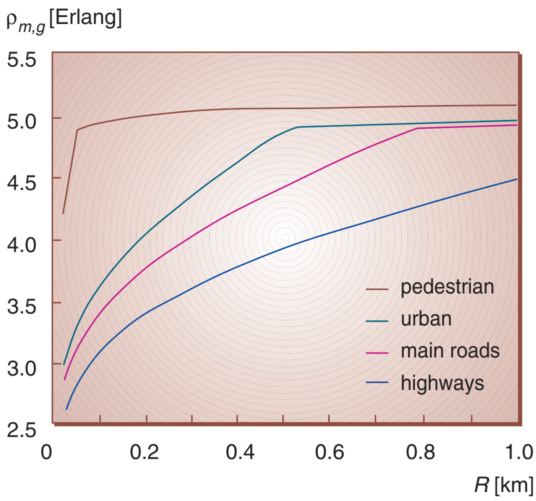

Figure 8 Traffic supported by m = 11 channels with g = 1

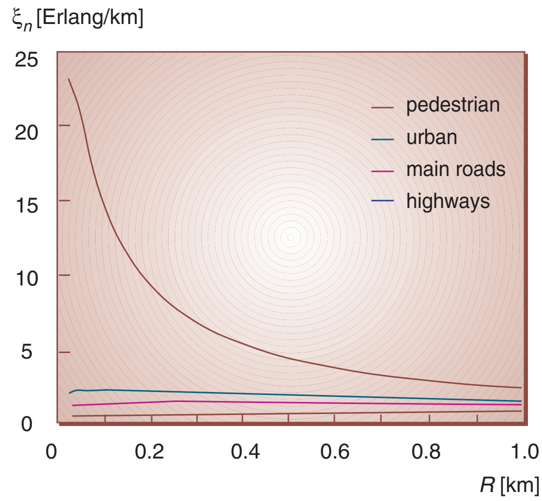

Figure 9 New calls traffic linear density, for m = 11 and g = 1

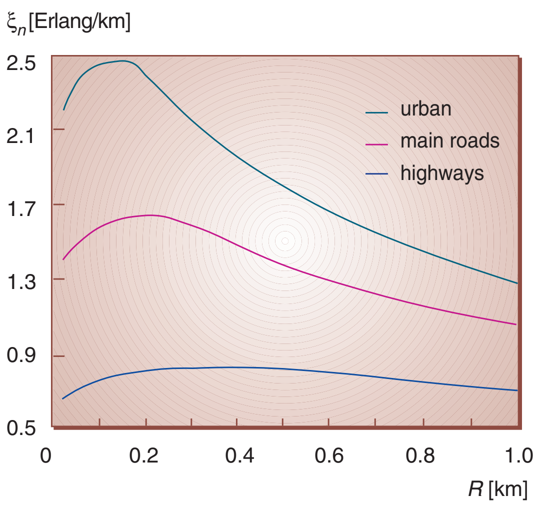

Figure 10 New calls traffic linear density, for m = 11 and g = 2

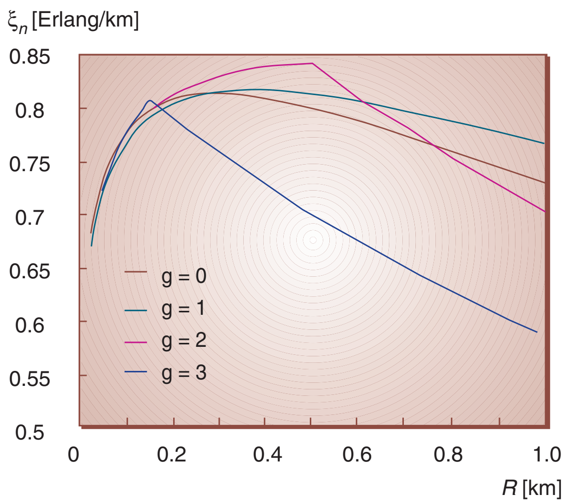

Figure 11 New calls traffic linear density for m = 11 and g = 0, 1, 2 and 3, in the highway scenario

Figure 11 presents $\xi_n(R)$ for the highway scenario for several values of g. One observes an improved new calls traffic linear density for $g = 2$ for $160 < R < 610$ m, the maximum $\xi_n = 0.84$ Erlang/km being obtained for $R_{opt} = 475$ m. An improvement of the new calls traffic linear density when $g = 3$ exists only for $130 < R < 160$ m, the maximum being obtained for $R_{opt} = 130$ m, $\xi_n = 0.81$ Erlang/km.

It is noticeable that the use of guard channels makes a difference in system performance, especially for high speed scenarios, where it allows us to overcome the problems associated with handover failure constraints. For these scenarios and for the typical coverage distances in MBS, the new calls traffic linear density is one order of magnitude below the values obtained for the pedestrian scenario (where it is approximately 10 – 15 Erlang/km), decreasing from 2.47 Erlang/km, in the urban scenario, down to 0.84 Erlang/km, in the highway scenario.

4 Conclusions

A microcellular communications system without guard channels for handover, with a linear coverage geometry, was first analyzed. Models to compute the supported traffic and the new

Table 3 Approximate values for R_{opt} and maximum values for ξ_n with m = 11

	R_{opt} [m]		ξ_n [/km]	
Scenarios	$g = 1$	$g = 2$	$g = 1$	$g = 2$
Urban	125	150	2.40	2.47
Main roads	175	250	1.60	1.65
Highways	375	475	0.82	0.84

calls traffic linear density as a function of velocity and cell length were examined. For a fixed blocking probability, one verifies that the new calls traffic linear density, which was used as a measure to system capacity, is upper limited by the average cross-over velocity of the associated scenario, having lower values for scenarios with high mobility, and varying differently depending on the average cross-over velocity. However, for actual scenarios the call-dropping probability constraints are not fulfilled in such conditions. Thus, in order to simultaneously verify the constraints for the blocking and the handover failure probabilities, it is necessary to consider lower blocking probabilities which leads to a decrease in the new calls traffic linear density with the decrease of R for such configurations. Feasible values for the new calls traffic linear density were obtained, where there are optimum values for the coverage distance that maximize it. These maxima correspond to lower values of the coverage distance for scenarios with lower mobility, being lower for scenarios with higher mobility.

In order to overtake the limitation associated with the case where no guard channels are used, configurations that use guard channels for handover were analyzed. Results were obtained for different values of the number of guard channels g. One concludes that, for the coverage distances foreseen for MBS, higher optimum values for the new calls traffic linear density are obtained for $g = 2$. However, for the highways scenario the corresponding coverage distances are larger than the foreseen cell lengths. It has also been verified that there is a degradation in system capacity, measured in Erlang/km, for higher and higher mobility scenarios.

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References

1 Fernandes, L. Developing a system concept and technologies for mobile broadband communications. *IEEE Personal Communications Magazine,* 2, (1), 1995, 54–59.

2 Velez, F, Correia, L M. Optimization criteria for cellular planning of mobile broadband systems in linear and urban coverages. In: *Proc. ACTS Mobile Communications Summit, Aalborg, Denmark,* Oct. 1997, 199–205.

3 Chlebus, E, Ludwin, W. Is handoff traffic really Poissonean? In: *Proc. of ICUPC' 95 – IEEE International Conference on Universal Personal Communications, Tokyo, Japan,* Nov. 1995, 348–353.

4 Jabbari, B. Teletraffic aspects of evolving and next-generation wireless communication networks. *IEEE Personal Communications Magazine,* 3, (6), 1996, 4–9.

5 Sidi, M, Starobinski, D. New call blocking versus handoff blocking in cellular networks. *Wireless Networks,* 3, (I), 1997, 15–27.

6 Correia, L M et al. *Report on design rules for cell layout.* RACE Deliverable R2067/IST/2.2.3/DS/P/044.b1, RACE Central Office, Brussels, Belgium, 1994.

7 ITU-T. *Networks grade of service parameters and target values for circuit-switched public land mobile services.* ITU-T Recommendation E.771, Geneva, 1996.

8 Ross, K, Tsang, D. Teletraffic engineering for product-form circuit-switched networks. *Adv. Applied Probability,* 22, 1990, 657–675.

9 Guérin, R. Channel occupancy time distribution in a cellular radio system. *IEEE Transactions on Vehicular Technology,* 36, (3), 1987, 89–99.

10 Hong, D, Rappaport, S. Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and non-prioritized hand-off procedures. *IEEE Transactions on Vehicular Technology,* 35, (3), 1986, 77–92.

11 Yacoub, M D. *Foundations of mobile radio engineering.* CRC Press, Boca Raton, Florida, USA, 1993.

12 Silva, N, Brázio, J. Reduction in location management signalling by the use of subpopulation-tailored location area sizes. In: *Proc. of ICUPC' 96 – International Conference on Universal Personal Communications, Cambridge, Massachusetts,* USA, 1996, 602–606.

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