

# Capacity Trade-offs in Mobile Broadband Systems Using Guard Channels for High Mobility Handover

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## ABSTRACT

Models allowing the study of the influence of coverage distance and mobile 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. In order to cope with handover failure probability requirements, the use of guard channels for handover is assumed, mainly 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.

## I. INTRODUCTION

Mobile Broadband Systems will extend 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 and having dimensions of the order of a few hundreds of metres [2]; the use of microcells is also foreseen for main road scenarios.

The high mobility associated with the future MBS yields a teletraffic analysis, where both the new calls and the handover traffics must 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 may be 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 geometries, where mobiles travel randomly through cells located end-to-end, a new calls traffic linear density is considered,  $\xi_n$ . To have an insight into the trade-offs involved in the optimization procedure for MBS, the behaviour of  $\xi_n$  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: pedestrian, urban, main roads and highways.

Although MBS will be a multi-service system, providing mobile multimedia communications handling both bursty and constant-bit-rate traffic, in this paper only a single service will be taken into account, in order to simplify this first analysis of the problem; videotelephony at 34 Mb/s, which will have a large demand, is considered as example [5]. This analysis will be in any case useful in the computation of multi-service aggregated traffic, because the first step of this more general problem [6] consists of computing, for each type of traffic, the state probability as if it was the only kind of traffic in the system.

The remainder of the paper is organized as follows. In Section II, time parameters are described, and handover probability and cross-over rate are introduced; the approach followed in the design consists of using guard channels for handover as a solution to overcome limitations in system capacity imposed by the high mobility of terminals. In Section III, the characteristics of some main mobility scenarios are described and values for the average cross-over velocity are calculated. In Section IV, models for the computation of supported traffic and new calls traffic linear density are presented, and the dependence of the latter on  $R$  is highlighted. In Section V, the trade-offs involved in the design are described and results are obtained for the supported traffic, and for the new calls traffic linear density. Finally, some conclusions are drawn on the influence of mobility on handover traffic versus new calls traffic, and its consequences on the maximization of MBS capacity.

## II. TRAFFIC ANALYSIS

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, Fig. 1; a call comprises successive sessions  $\tau_1, \tau_2, \tau_3, \dots$  in cells traversed by the mobile, and its duration  $\tau$  follows an exponential distribution whose mean is  $\bar{\tau} = 1/\mu$  [4], where  $\mu$  is the service rate. The channel occupancy time  $\tau_c$  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 [7].

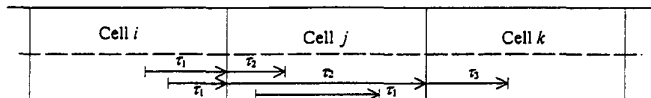


Fig.1 - Dwell time and channel occupancy time.

The cell dwell time  $\tau_h$  is the residing time of a mobile within a cell. Further assuming that the dwell time is exponentially distributed with mean  $\bar{\tau}_h = 1/\eta$ , where  $\eta$  is the cross-over rate, 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

$$\bar{\tau}_c = \frac{1}{\mu_c} = \frac{1}{\mu + \eta} \quad (1)$$

the probability of handover being given by

$$P_h = \text{Prob}\{\tau > \tau_h\} = \frac{\eta}{\mu + \eta} = \frac{\bar{\tau}_c}{\bar{\tau}} \quad (2)$$

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

$$\eta = \frac{1}{\int_0^{v_{\max}} \left(\frac{2R}{v}\right) \cdot f(v) dv} \quad (3)$$

$v$  being the velocity and  $f$  the velocity probability density function (note that in this linear geometry the cells length 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 handover failure probability 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. 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 channel  $m = g + c$  is considered, where  $c$  is the number of channels to support both new and handover calls.

If guard channels for handover were not used, the call dropping probability,  $P_d$ , would be given by [4]

$$P_d = P_h P_{hf} \sum_{i=0}^{\infty} P_h^i (1 - P_{hf})^i \quad (4)$$

where  $i$  designates the order of the handover and  $P_{hf}$  is the handover failure probability; for small values of  $P_{hf}$ , it can be approximated by

$$P_d = \frac{\eta}{\mu} \cdot P_{hf} \quad (5)$$

Still in this case  $P_{hf}$  would be equal to the blocking probability,  $P_b$  [8], which imposes a strong limitation, because  $P_b$  would be as low as  $P_d$  determines [9]. The use of guard channels for handover allows to overtake this limitation because  $P_b$  and  $P_{hf}$  will be decoupled [8]; 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  $\lambda$ , the number of channels at each cell  $m$ , besides  $v$  and  $\mu$ . 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 geometries [10]) will be considered here as first step to a more complicated (and closer to reality) analysis.

## III. MOBILITY SCENARIOS

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

Table 1 - Mobility scenarios.

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

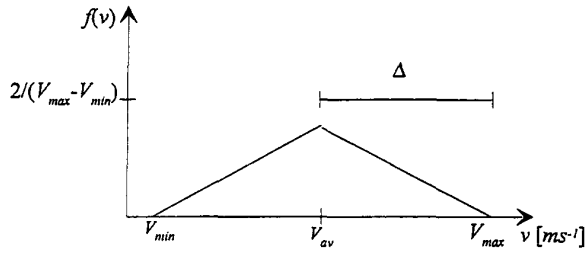


Fig. 2 - Velocity probability density function.

The probability density function is given by

$$f(v) = \begin{cases} \frac{1}{\Delta^2} \cdot [v - (V_{av} - \Delta)], & V_{av} - \Delta \leq v \leq V_{av} \\ -\frac{1}{\Delta^2} \cdot [v - (V_{av} + \Delta)], & V_{av} \leq v \leq V_{av} + \Delta \\ 0 & , \text{otherwise} \end{cases} \quad (6)$$

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

$$\eta = \left\{ \frac{2R}{\Delta^2} \left[ (V_{av} + \Delta) \cdot \ln\left(\frac{V_{av} + \Delta}{V_{av}}\right) - (V_{av} - \Delta) \cdot \ln\left(\frac{V_{av}}{V_{av} - \Delta}\right) \right] \right\}^{-1} \quad (7)$$

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

$$\eta = \frac{V_{av}}{2 \cdot \ln(2)} \cdot \frac{1}{(2R)} \quad (8)$$

Defining the average cross-over velocity  $\eta^*$  as

$$\eta^* = \eta \cdot (2R) \quad (9)$$

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

Table 2 - Average cross-over velocity.

Scenario	$\eta^* [\text{m} \cdot \text{s}^{-1}]$
Pedestrian	0.72
Urban	7.21
Main roads	10.82
Highways	21.24

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

#### IV. TRAFFIC LINEAR DENSITY

Assuming that the handover traffic can be approximate by a Poisson process [3] and that the new calls one has the same distribution, which is valid for a number of users in a cell much larger than the supported traffic, when no queueing of new or handover calls is performed the blocking and handover failure probabilities are given by [4]

$$P_b = \frac{(\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h^k}{k!}}{\sum_{k=0}^{c-1} \frac{(\rho_n + \rho_h)^k}{k!} + (\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h^k}{k!}} \quad (10)$$

$$P_{hf} = \frac{(\rho_n + \rho_h)^c \frac{\rho_h^g}{(c+g)!}}{\sum_{k=0}^{c-1} \frac{(\rho_n + \rho_h)^k}{k!} + (\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h^k}{k!}} \quad (11)$$

where  $\rho_n$  is the new calls traffic and  $\rho_h$  is the handover one; 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 [4]

$$\rho_n = \frac{\mu}{\eta + \mu} \cdot \rho_{m,g} = \frac{2\mu R}{\eta^* + 2\mu R} \cdot \rho_{m,g} \quad (12)$$

$$\rho_h = \frac{\eta}{\eta + \mu} \cdot \rho_{m,g} = \frac{\eta^*}{\eta^* + 2\mu R} \cdot \rho_{m,g} \quad (13)$$

where the dependence on the cell length has been made explicit by introducing the average cross-over velocity. The new calls traffic linear density is then given by

$$\xi_n = \frac{\rho_n}{2R} = \frac{1}{1 + 2\mu R/\eta^*} \cdot \frac{\mu}{\eta^*} \cdot \rho_{m,g} \quad (14)$$

which, for a fixed  $\rho_{m,g}$  and a given  $\mu$ , is upper bounded by  $\mu/\eta^*$ , decreasing with the increase of the cross-over velocity.

#### V. DESIGN TRADE-OFFS

The examples given here were obtained for  $m = 11$  [2],  $P_b = 2\%$ ,  $P_d = 0.5\%$  [11],  $\mu = 1/180 \text{ s}^{-1}$ , and values for  $V_{av}$  and  $\Delta$  in Table 1. 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 [9]. However, the corresponding call-dropping probability constraints associated with (5) and with  $P_b$  being equal to  $P_{hf}$ , Fig. 3, are only fulfilled in the pedestrian scenario, and only for  $R > 300 \text{ m}$ ; 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  $\xi_n$  while  $R$  decreases. In order to obtain results for the supported traffic the procedure was the following: taking  $P_d = 0.5\%$ , (5) was used to get a value for  $P_{hf}$ ; with this  $P_{hf}$  value and with  $P_b = 2\%$ , (10) and (11) were solved separately for the supported traffic  $\rho_{m,g}$  (using (12) and (13)), and the respective values,  $\rho_{P_b}$  and  $\rho_{P_{hf}}$ , were obtained; in order to cope with both probability requirements, the minimum of these two must be taken.

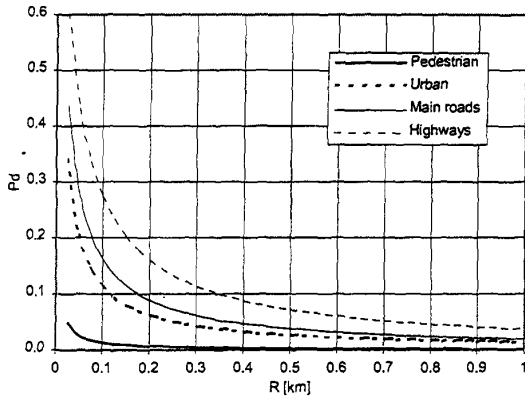


Fig. 3 - Call-dropping probability for  $g = 0$ .

While  $\rho_{pb}(R)$  is almost constant with  $R$ , right part of the curves in Fig. 4 (example for  $g = 1$ ),  $\rho_{phf}(R)$  increases with  $R$  (since it was obtained according to (5), and  $\eta$  depends on  $R$ , as in (8) and (9)), 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 be seen as well that the breakpoint occurs for increasing values of  $R$  for faster and faster mobiles.

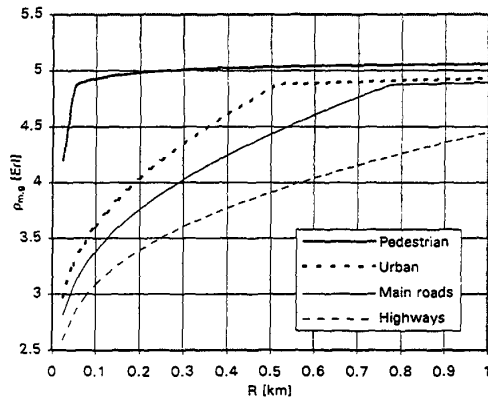


Fig. 4 - Traffic supported by  $m = 11$  channels with  $g = 1$ .

As it 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  $\rho_{phf}$  and keep it lower than  $\rho_{pb}$ , mainly for the scenarios with high mobility (urban, main roads and highways).

For given values of  $m$  and  $g$ , one can then obtain the curves for the new calls traffic linear density  $\xi_n(R)$  according to (14); Figs. 5 and 6 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  $R$ , one basically observes that it follows the behaviour of the ratio at the right member from (14). 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, corresponding, for design purposes, 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.

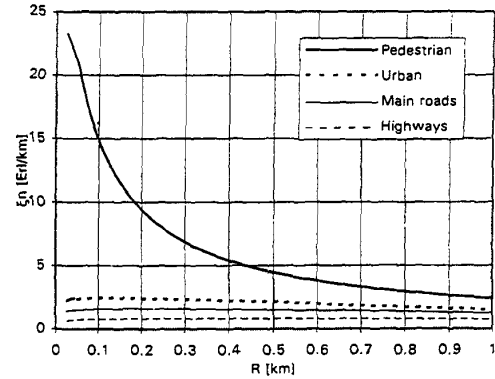


Fig. 5 - New calls traffic linear density, for  $m = 11$  and  $g = 1$ .

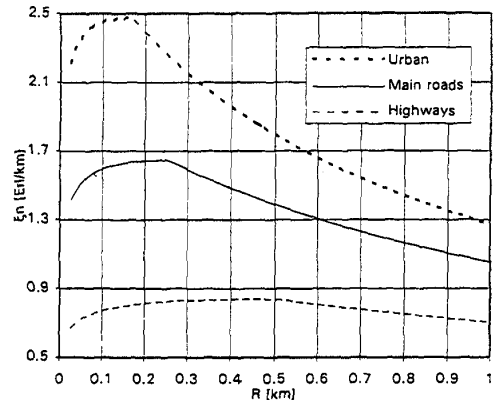


Fig. 6 - New calls traffic linear density, for  $m = 11$  and  $g = 2$ .

Table 3 - Approximate values for  $R_{opt}$  and maximum values for  $\xi_n$  with  $m = 11$ .

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

Fig. 7 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  $\xi_n = 0.84$  Erl/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,  $\xi_n = 0.81$  Erl/km.

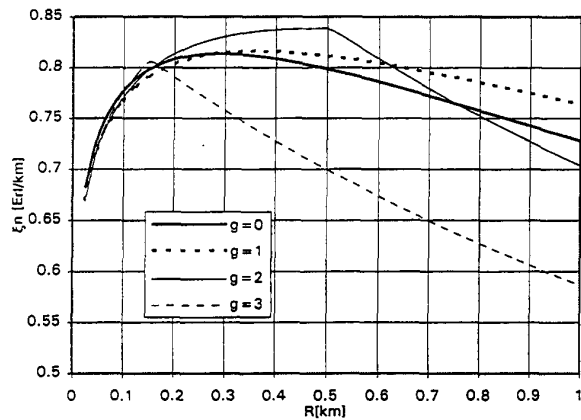


Fig. 7 - New calls traffic linear density, for  $m = 11$  and  $g = 0, 1, 2$  and  $3$ , in the highway scenario.

It is noticeable that the use of guard channels makes a difference in system performance, specially for high speed scenarios, where it allows 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.

## VI. CONCLUSIONS

A microcellular communications system using guard channels for handover, with a linear coverage geometry, was analyzed, and four typical scenarios for MBS were considered. Models to compute the supported traffic and the new calls traffic linear density, as a function of velocity and cell length, were examined. 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 Erl/km, for higher and higher mobility scenarios.

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