Mixed Media Cellular Systems

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***Abstract*— A voice/data cellular system is studied in this work. Analytical methods are used based on generating functions techniques. An extended simulation analysis it was also carried out, defining the main performance parameters and their impact on system behaviour. The limits of analytical study are investigated and solutions through simulation methods are proposed.**

I. Introduction

FUTURE communication networks are expected to handle a variety of data traffic types, including digital voice, facsimile, video, file transfer and interactive information services. These services will be offered not only by stationary terminals but also by land mobile terminals which will be totally integrated into the public communications networks.

Cellular mobile networks have been studied extensively last years. Frequency assignment techniques, channel access models, transmission quality, standards for interfacing with the wired network as well as traffic management are some of the topics gained attention. Especially, referring to the last topic, a mathematical model has been developed [1]-[3] adequate for traffic analysis of mobile communications systems. The important parameters of voice communication systems, i.e. blocking probability of new calls, handoff requirement probability, forced termination probability e.t.c, have been stated as functions of the system state probabilities. The cases of vehicular as well as portable terminals have been covered. But as far as we know there is no analysis for mixed media cellular systems -voice, data, video- which will be widely used in the near future.

In this work, we extend the mathematical model of [1] for the purpose of studying a voice-data cellular system. In the second section the mathematical model is presented and the main performance parameters are evaluated. Simulation analysis is carried out and results are presented in the third section. Conclusion and suggestions for further analysis are finally stated.

II. Mathematical model

A. System Description

Without loss of generality we concentrate on the study of a highway cellular system, Fig. 1, where the base stations are installed at the center of rectangular cells of length L. Frequencies in successive cells are different to each other so we do not deal with interference effects. We assume two streams -voice calls and data packets- of Poisson arrivals originated at each cell with rates λ_{nv} and λ_{np} and average service durations $1/\mu_v$ and $1/\mu_p$. The two processes being independent, a cumulative service time can be defined by the wellknown hyperexponential formula $T_\mu = 1/\mu = 1/\mu_v + 1/\mu_p$. At each cell we have also arrivals of handoff calls and packets, assumed Poisson with rates λ_{vH} and λ_{pH}.

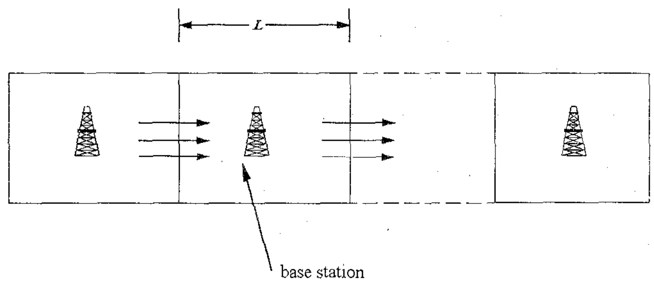

Fig. 1. Schematic diagram of a cellular highway system.

The system rule is described in Fig.2, where in each cell there are C-C_h channels available for new calls and packets, C channels available for handoff calls and packets and an infinite queue. If there is no free channel after a handoff requirement a call is forced into termination while a packet is placed in the queue in FIFO order. New packets that do not succeed to get a channel in the cell of their arrival are blocked and cleared from the system. Once they have got a channel they remain in the system, possibly transferred from one queue to another, till they finish their service.

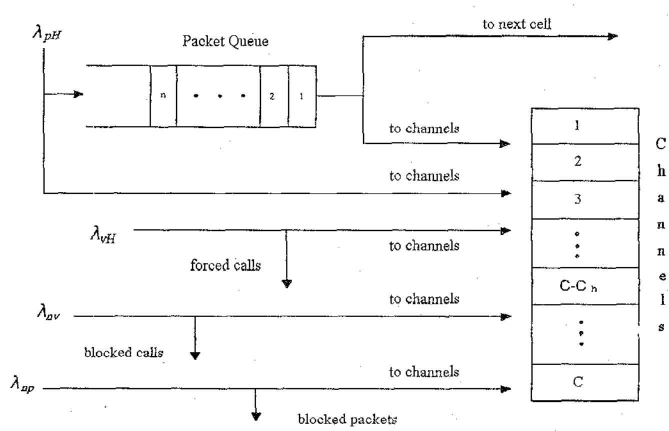

Fig. 2. Operation rule for a mixed cellular system.

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B. Performance parameters

In the following we define the main performance parameters of the system which are: a)the blocking probability P_B of new voice calls (the average fraction of new calls that cannot find a channel and are cleared from the system). b)the probability of forced termination P_{fh} of handoff voice calls (the average fraction of handoff attempts which are unsuccessful). c)the delay probability P_D of a handoff packet, (the probability that a handoff packet will not get a channel and remain in the queue all the time it is transferred through a cell). d)the mean waiting time in the queue D_q of handoff packets and e)the queueing probability P_q of a handoff packet where P_q denotes the probability that a handoff packet enters the queue (but probably it will get a channel anytime it is transferred through the cell).

Except from the unencumbered service time $1/\mu$ we need also to define the random variable T_n being the channel holding time of a new call or packet in the cell of its arrival and the random variable T_h being the channel holding time of a handoff call or packet in a cell after a successful handoff.

The channel assigned to a call or packet will be held until either the service is completed in the cell of the assignment or the vehicle moves out of the cell before service completion. Since the distribution probabilities of channel holding times of handoffs (T_h) and new arrivals (T_n) are different from each other, the channel holding time of a new arrival T_{Hn} and the channel holding time of a handoff arrival T_{Hh} will be

$$T_{Hn} = min(T_\mu, T_n)$$
$$T_{Hh} = min(T_\mu, T_h) \tag{1}$$

Assuming independence of T_μ, T_n and of T_μ, T_h the distribution functions of T_{Hn} and T_{Hh} are given by

$$F_{T_{Hn}}(t) = F_{T_\mu}(t) + F_{T_n}(t)\left[1 - F_{T_\mu}(t)\right] \tag{2}$$

$$F_{T_{Hh}}(t) = F_{T_\mu}(t) + F_{T_h}(t)\left[1 - F_{T_\mu}(t)\right] \tag{3}$$

Then the distribution function of the total channel holding time T_H in a cell is

$$F_{T_H}(t) = F_{T_\mu}(t) +$$
$$+\left(1 - F_{T_\mu}(t)\right)\frac{(\lambda_{nv}+\lambda_{np})(1-P_B)F_{T_n}(t)+}{(\lambda_{nv}+\lambda_{np})(1-P_B)+\lambda_{vH}(1-P_{fh})+\lambda_{pH}(1-P_DP_q)}$$
$$+\frac{\left[\lambda_{vH}(1-P_{fh})+\lambda_{pH}(1-P_DP_q)\right]F_{T_h}(t)}{(\lambda_{nv}+\lambda_{np})(1-P_B)+\lambda_{vH}(1-P_{fh})+\lambda_{pH}(1-P_DP_q)} \tag{4}$$

and

$$F_{T_H}(t) = F_{T_\mu}(t) + \left(1 - F_{T_\mu}(t)\right)\frac{F_{T_n}(t) + \gamma_c F_{T_h}(t)}{1+\gamma_c} \tag{5}$$

where γ_c is the ratio of the average successful handoff attempt rate to the average successful new arrival attempt rate, given by

$$\gamma_c \equiv \frac{\lambda_{vH}(1-P_{fh})+\lambda_{pH}(1-P_DP_q)}{(\lambda_{nv}+\lambda_{np})(1-P_B)} \tag{6}$$

Now we assume that T_n and T_h are exponentially distributed with means $\overline{T}_n = 1/\mu_n$ and $\overline{T}_h = 1/\mu_h$. With the above assumption the distribution and density functions of T_H are given

$$F_{T_H}(t) = \left[1 - e^{-\mu t}\right] + e^{-\mu t}\left[1 - \frac{e^{-\mu_n t} + \gamma_c e^{-\mu_h t}}{1+\gamma_c}\right] \tag{7}$$

$$f_{T_H}(t) = \frac{\mu+\mu_n}{1+\gamma_c}e^{-(\mu_n+\mu)t} + \frac{\gamma_c}{1+\gamma_c}(\mu+\mu_h)e^{-(\mu_h+\mu)t} \tag{8}$$

The mean value of $f_{T_H}(t)$ is equal to

$$\overline{T}_H = \int_0^\infty t f_{T_H}(t)dt = \frac{1}{1+\gamma_c}\left[\frac{1}{\mu+\mu_n} + \frac{1}{\mu+\mu_h}\right] \tag{9}$$

According to the previous description the state diagram of our system is given in Fig.3 and the state probabilities are given by:

$$P_0 = \left[\sum_{k=0}^{C-C_h}\frac{(\lambda_{nv}+\lambda_{np}+\lambda_{vH}+\lambda_{pH})^k}{k!\,\mu_H^k} + \right.$$
$$+\sum_{k=C-C_h+1}^{C}\frac{(\lambda_{nv}+\lambda_{np}+\lambda_{vH}+\lambda_{pH})^{C-C_h}}{k!\,\mu_H^k}(\lambda_{vH}+\lambda_{pH})^{k-(C-C_h)} +$$
$$\left.+\sum_{k=C+1}^{\infty}\frac{(\lambda_{nv}+\lambda_{np}+\lambda_{vH}+\lambda_{pH})^{C-C_h}\lambda_{pH}^{k-(C-C_h)}}{C!\,\mu_H^C\prod_{i=1}^{k-C}\left[C\mu_H + i\mu_D\right]}\right]^{-1} \tag{10}$$

Then the blocking probability P_B of a new arrival either voice or packet is

$$P_B = \sum_{j=C-C_h}^{\infty} P_j \tag{12}$$

the handoff voice failure probability P_{fh} is

$$P_j = \begin{cases} \dfrac{(\lambda_{nv} + \lambda_{np} + \lambda_{vH} + \lambda_{pH})^j}{j!\,\mu_H^j} P_0 & 1 \le j \le C - C_h \\ \dfrac{(\lambda_{nv} + \lambda_{np} + \lambda_{vH} + \lambda_{pH})^{C-C_h}}{j!\,\mu_H^j} \left(\lambda_{vH} + \lambda_{pH}\right)^{j-(C-C_h)} P_0 & C - C_h + 1 \le j \le C \\ \dfrac{(\lambda_{nv} + \lambda_{np} + \lambda_{vH} + \lambda_{pH})^{C-Ch_h} \lambda_{pH}^{j-(C-C_h)}}{C!\,\mu_H^C \prod_{i=1}^{j-C} [C\mu_H + i\mu_D]} P_0 & j \ge C+1 \end{cases} \tag{11}$$

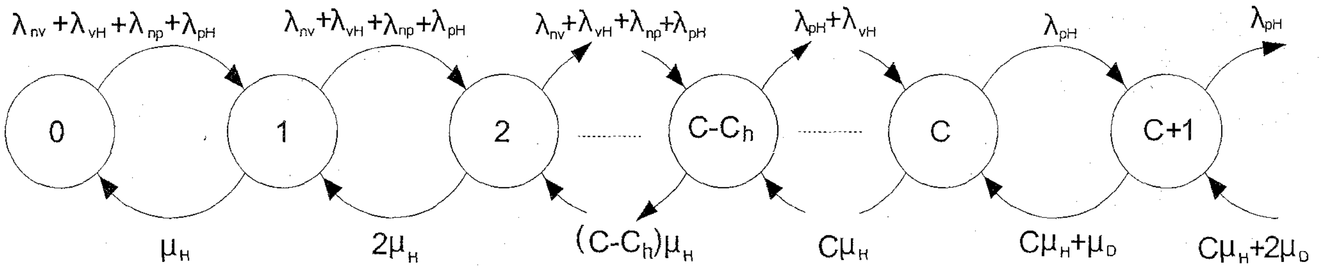

Fig. 3. State transition diagram of a base station.

$$P_{fh} = \sum_{j=C}^{\infty} P_j \tag{13}$$

and the packet handoff queueing probability is equal by definition to P_{fh}

$$P_q = \sum_{j=C}^{\infty} P_j \tag{14}$$

Once the state probabilities have been evaluated the mean number of handoff packets in the queue is given by

$$N_q = \sum_{i=C+1}^{\infty} iP_i P_o P_s \tag{15}$$

where P_o is the probability that an attempt entering the queue in position i will reach the first position of the queue and P_S is the probability to get a channel while in the first position.

The probabilities P_S and P_o are given in (34) and (35) of [2]. Thus we have

$$N_q = \sum_{i=1}^{\infty} iP_{C+i} P\left(i-1 \middle| i\right) P_s =$$

$$= \sum_{i=1}^{\infty} iP_{C+i} \prod_{k=1}^{i-1} \left[1 - \left(\frac{\mu_Q}{C\mu_H + \mu_Q} \right) \left(\frac{1}{2} \right)^k \right]^{i-k} \left(\frac{\mu_Q}{C\mu_H + \mu_Q} \right)^i \tag{16}$$

We assume that the random variable W which denotes the waiting time in the queue follows an exponential distribution with mean $1/w$, given by Little's formula

$$\lambda_{hp} \frac{1}{w} = N_q \tag{17}$$

Now we define the random variable T_D which denotes the time duration which an arrival is allowed to reside in the cell. This variable depends on system structure parameters such as the cell length and the vehicle speed. We assume that T_D follows an exponential distribution with mean $1/\mu_D$.

Then the probability P_D is the probability that the allowed residing time in the cell is less than the necessary waiting time W in the queue (to get service), that is

$$P_D = Prob\{T_D < W\} = \int_0^\infty [1 - F_W(t)] f_{T_D}(t) dt =$$

$$= \int_0^\infty e^{-wt} f_{T_D}(t) = \frac{\mu_D}{w + \mu_D} \tag{18}$$

The handoff requirement probability for new arrivals P_N that is the probability that the unencumbered session duration exceeds the residing time in the cell of the arrival is given as follows

$$P_N = Prob\{T_\mu > T_n\} = \int_0^\infty [1 - F_{T_\mu}(t)] f_{T_n}(t) dt =$$

$$= \int_0^\infty e^{-\mu t} f_{T_n}(t) = \frac{\mu_n}{\mu + \mu_n} \tag{19}$$

Similarly the handoff requirement probability for a handoff arrival P_H is equal to

$$P_H = Prob\{T_\mu > T_h\} = \int_0^\infty [1 - F_{T_\mu}(t)] f_{T_h}(t) dt =$$

$$= \int_0^\infty e^{-\mu t} f_{T_h}(t) = \frac{\mu_h}{\mu + \mu_h} \tag{20}$$

We also need to evaluate the number of times N that a packet requires a handoff (or equally the number of cells it crosses till the service completion). The packet will require exactly $N=k$ handoffs if all of the following events occur: a)it is a nonblocked packet arrival b)it requires the kth handoff, and c)it is completed before another handoff is needed. This probability is

$$Prob\{N = k\} = \frac{\lambda_{np}}{\lambda_{np} + \lambda_{nv}} P_N P_H^{k-1} (1 - P_H) \tag{21}$$

The mean value of N is found to be

$$\overline{N} = \sum_{k=1}^{\infty} \frac{\lambda_{nv}}{\lambda_{nv} + \lambda_{np}} k P_N P_H^{k-1} (1 - P_H) = \frac{\lambda_{nv}}{\lambda_{nv} + \lambda_{np}} \frac{1}{1 - P_H} \tag{22}$$

And finally the total mean queueing delay of a packet is given by

$$\overline{D}_q = \overline{N} P_q \left[\frac{1}{w} (1 - P_D) + \frac{1}{\mu_D} P_D \right] \tag{23}$$

III. Simulation Analysis

A computer simulation program was developed in order to verify the analytical results and study the behaviour of the system and its sensitivity to parameters variability. A highway of 25 cells was examined and the statistical results were obtained from the central 10 cells. The system specification was the following: 1) All cells were rectangulars with length L=1000 m. 2) The velocity was taken to follow a truncated normal distribution with a mean value υ_m= 15 m/sec, a standard deviation 5 m/sec, a maximum speed υ_{max}= 20 m/sec and a minimum speed υ_{min}= 10 m/sec. This speed remains constant until the vehicle crosses the cell. 3) The service time had an exponential distribution, its mean value being variable. And 4) C=44 channels were available for each cell with C_h=10 channels for handoffs. All the events were randomly generated by the appropriate distribution functions. The location of the new arrivals in the cell was generated randomly under a uniform distribution.

The simulation program was written in C and run on VAX 9000. Statistics were collected for 3 h of simulated system after the system reached the steady state.

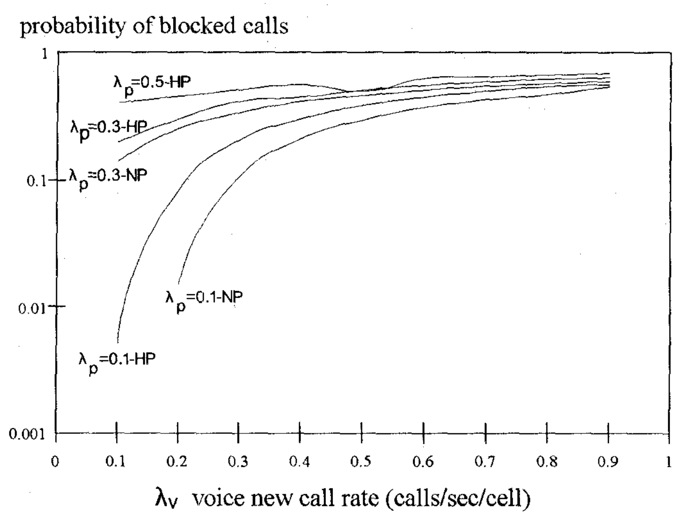

Fig. 4. Probability of blocked calls. In all subsequent figures λ_p= new data packet rate (packets/sec/cell).

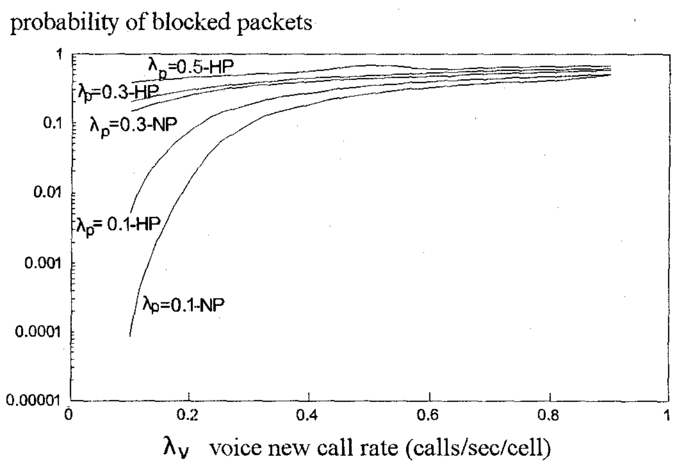

Fig. 5. Probability of blocked packets.

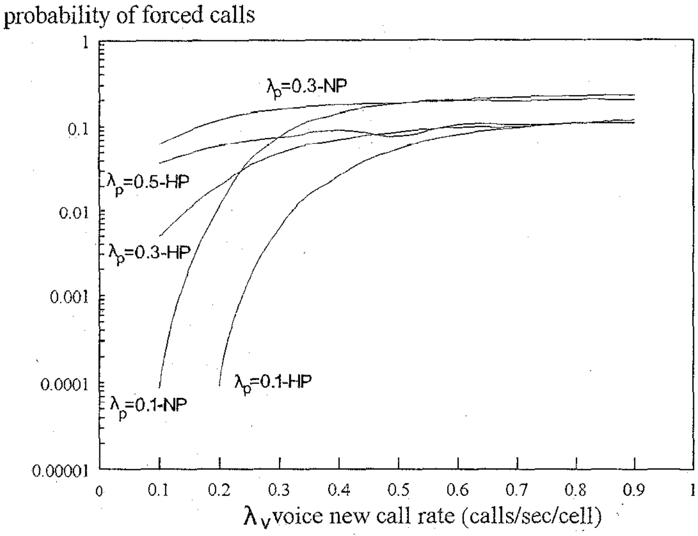

Fig. 6. Probability of forced calls.

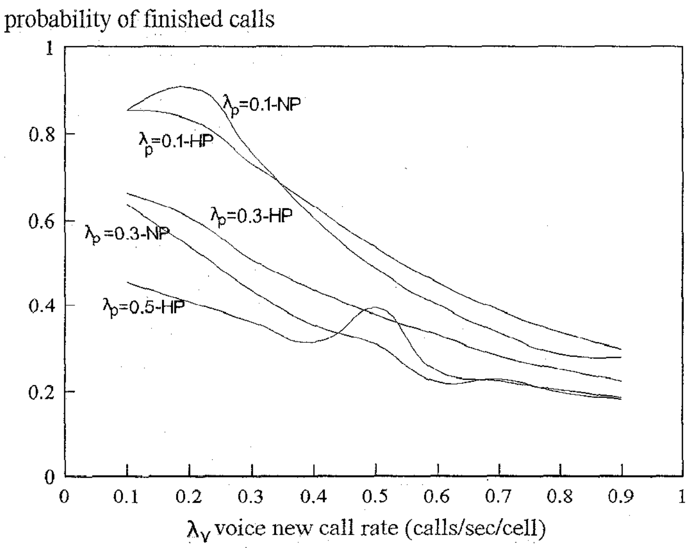

Fig. 7. Probability of finished calls.

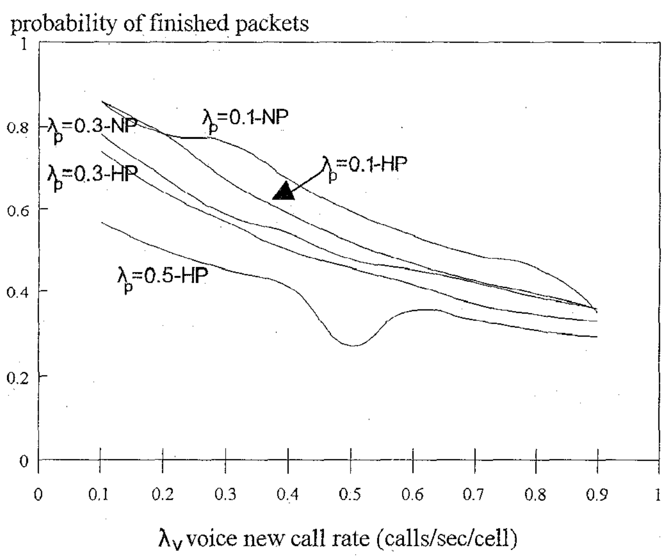

Fig. 8. Probability of finished packets.

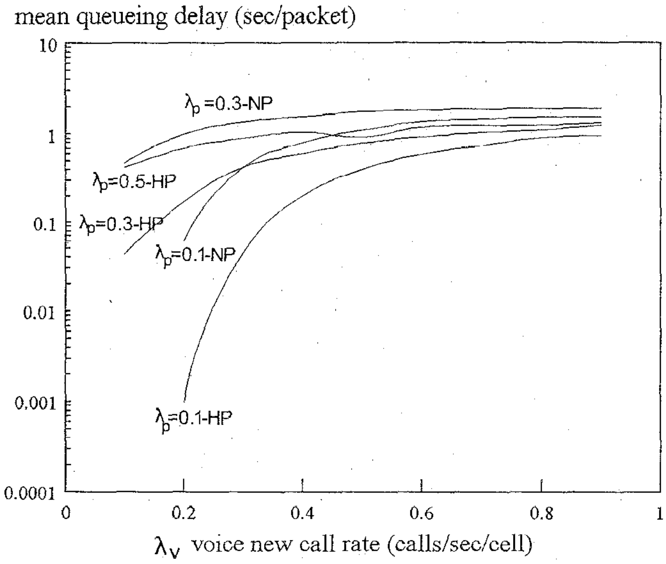

Fig. 9. Mean queueing delay.

In the following we present some of the simulation results. In Fig.4-Fig.9 the probabilities of blocked calls and packets, forced calls, finished calls and packets and the mean queueing delay of packets are presented as functions of new call arrival rate in Non-Priority Scheme (*NP*, $C_h=0$), and in Handoff Priority (*HP*, $C_h>0$) Scheme. The influence of packet loading is clearly shown as well as the influence of the priority given on handoff packets. In Fig.10 the comparative performance of the main measures of the system is given, for a better interpretation of the steady state operation. We notice that, even under light data loading, congestion effects are early noticed ($\lambda_{nV}=0.6$). A supplementary study was made considering the effects of service time variations on system performance. In Fig.11-Fig.12 we present these effects on the mean packet queueing delay and on the probability for forced call termination which are of main interest.

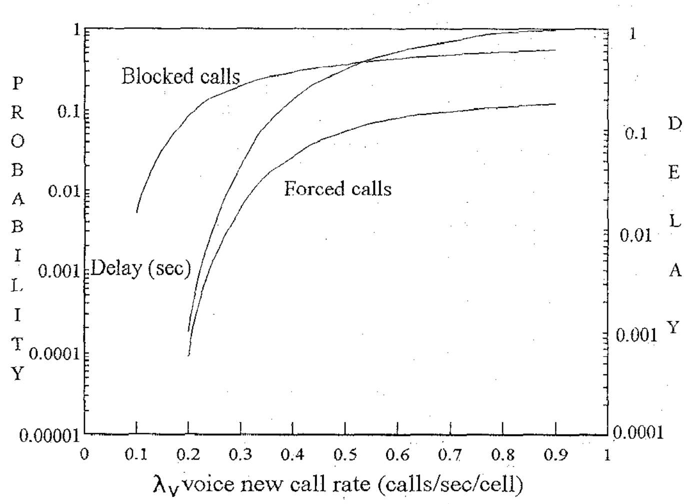

Fig. 10. Comparative performance of the main measures.

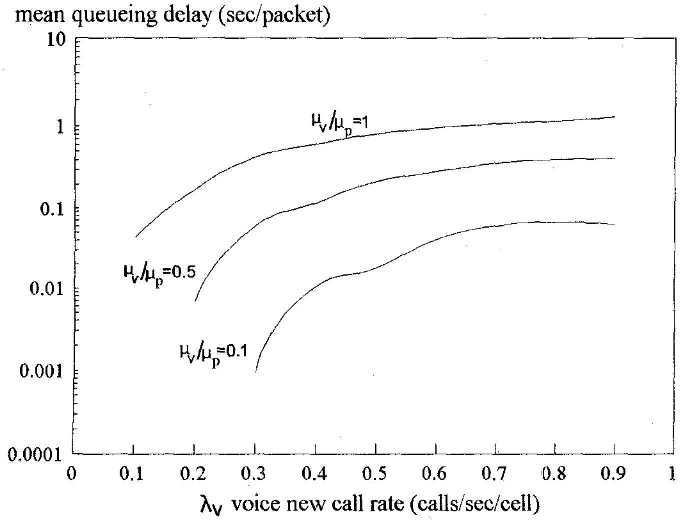

Fig. 11. Mean queuing delay for different service times.

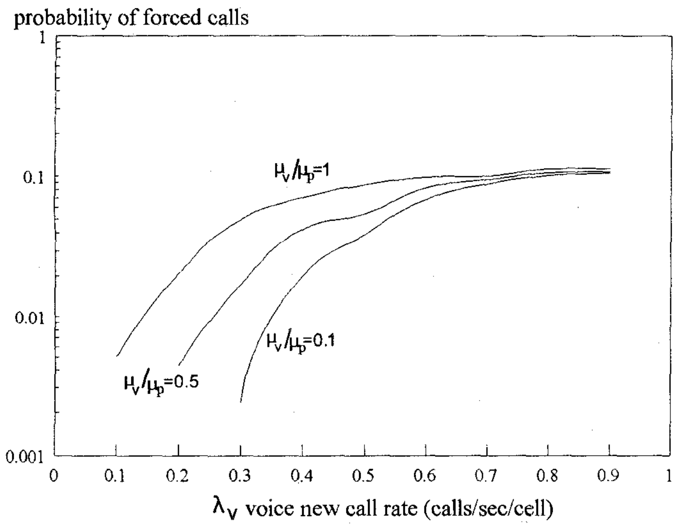

Fig. 12. Probability of forced calls for different service times.

Simulation results are found to be very satisfactory and helpful in optimising the system performance.

V. Conclusions

A mixed media cellular system has been studied and evaluated. The main performance parameters and their influence to system behaviour were studied. The main result of this study is that mixed media cellular systems are very complex and hard to analyze but the efforts are not trivial since these systems will be widespread soon. Analytic study is very hard to accomplish even for the simple case we have described. The cases of preemptive priority of voice over data as well as of "multilayer" cellular systems (macrocells covering microcells) are very difficult to be analysed by this model and two or three dimensional models are probably more effective. Work on this direction is currently carried out. Finally broadband services - video - must be by some means incorporated in the traffic analysis.

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