ESTIMATES OF MULTICARRIER CDMA SYSTEM CAPACITY

Tony Dean
Phil Fleming
Alexander Stolyar

Motorola, Inc.
1501 West Shure Drive
Arlington Heights, Illinois 60004, U.S.A.

ABSTRACT

As CDMA systems reach capacity, infrastructure providers are extending them by offering multicarrier capability. The capacity of an n-carrier CDMA system should be at least n times the capacity of a single-carrier system. We estimate the additional capacity that can be achieved by using carrier assignment disciplines. We produce the estimates from the CDMA System Static Simulator by pre-processing the simulator inputs and post-processing its outputs. The estimates are of capacities of multicarrier systems using simple carrier assignment disciplines, and of wideband CDMA systems. The latter estimates constitute an upper bound on the capacity of a multicarrier system with any carrier assignment discipline.

1 INTRODUCTION

As CDMA cellular systems reach capacity, cellular providers are offering multicarrier systems to extend capacity. Typical initial offerings assign mobiles to carriers at random, so the capacity of an *n*-carrier system is *n* times the capacity of a 1-carrier system. However, the *potential* capacity of a multicarrier CDMA system is a non-linear function of the number of carriers, because intelligent carrier assignment disciplines can exploit the trunking efficiency of the multiple carriers. In fact, up to 8% of additional capacity per carrier can be realized.

Among the conceptually simplest of carrier assignment disciplines are:

- **random carrier (RC):** The system assigns an initiating (i.e., originating or terminating) mobile to a random carrier.
- **round robin (RR):** The system maintains an ordered list of carriers, and an index of the next available carrier. The system assigns the next initiating mobile to the next available carrier, and increments the next carrier field. When incrementing takes the index

beyond the end of the list, the index is reset to the beginning of the list.
- **least load (LL):** The system maintains base site link counts (i.e., number of assigned walsh codes) for each carrier, and assigns an initiating mobile to a carrier with minimal link count. The assignment is random among carriers with minimal link count.
- **full sharing (FS)**: An imaginary discipline in which the system assigns the initial and each soft/softer handoff link request to the least loaded carrier, even if links are on separate carriers.

As LL is very simple to implement and promises to realize much of the capacity of the FS discipline, we concentrated our study on the LL discipline. Two other assignment disciplines of note are analogous to LL in that they assign initiating mobiles to a carrier with some minimal resource. These are:

- **least power**: The maintained resource is total allocated forward power.
- **least noise rise**: The maintained resource is total reverse noise rise.

Simulation has shown the least power discipline to be little better than the LL discipline. The least noise rise discipline is probably the most difficult to implement, and we have made no estimates of its capacity benefits.

In the interest of simplicity, we have restricted our investigation to ubiquitously deployed multicarrier systems. In contrast, many cellular operators are installing multicarriers non-ubiquitously, i.e., only in areas where traffic is heavy. As this involves rings of collar cells, pilot beacons, and other complications in support of hard hand-offs between the single and multicarrier zones, we will address non-ubiquitous deployment in a later study. In the meantime, the results for ubiquitously deployed multicarrier systems provide insight into the behavior of

non-ubiquitously deployed systems, especially in the center of large multicarrier zones.

2 DEFINITIONS AND CONVENTIONS

The capacity of a system refers to the maximum amount of service it can provide. For cellular systems, one usually measures service in terms of the number of mobiles served or coverage provided. We are interested in the number of mobiles served. In this context, we consider a mobile to be *served* if both averages of forward and reverse link frame error rates (FER) are 2% or less. The *outage* of the system is then the ratio of the number of mobiles *not* served to the total number of mobiles. The *capacity* of the system is the number of mobiles served at a given outage, typically 1%, 2%, or 5%. Typically, we quote capacity in mobiles served per carrier per sector. We use the word *sector* in its most general sense, i.e., the coverage of a single antenna. In this context, the *sectors* of an omni system are identical to its cells.

3 THE MOTOROLA CDMA STATIC SYSTEM SIMULATOR

Earlier studies of multicarrier CDMA, such as (Fleming and Stolyar, 1998) and (Fleming and Simon, 1998) have estimated capacity by using analytic models. In this study, we used the CDMA Static System Simulator (CSSS) (Motorola Technical Education & Documentation, 1996), which is a component of Motorola's Net Plan cellular planning tool. Parameters of the CSSS model include (but are not limited by)

- System characteristics, such as RF propagation, power control parameters, and target and outage forward/reverse FER thresholds;
- Sector characteristics, such as position, pilot, page, and sync channel powers;
- Mobile characteristics, such as statistical distributions of position, speed, power class, delay spread, and number in system.

The CSSS generates Monte Carlo 'snapshots' of the model CDMA system in operation. Prior to each snapshot, the CSSS generates a random number of mobiles and places them at random positions with random speeds, power classes and delay spread characteristics. The process of creating the snapshot has come to be known as a 'drop', evoking the image of mobiles being randomly dropped into the geometry of the simulation space. Once the drop has been created, the CSSS attempts to solve the forward and reverse power control equations by iteratively modifying the forward and reverse powers and by making and breaking soft/softer handoff links. The output of each drop consists of system state descriptions of each mobile and

base site, including fractions of mobiles meeting the FER criteria both by base site and over the entire system. The resulting outputs simulate what might be seen if one collected the same data at regular, uncorrelated intervals from an actual CDMA system.

After each drop, the CSSS produces a *Monte Carlo statistics* file, which describes the state of the model after power control. The file is named `desc.out<n>,` where *n* is the number of the drop, and is comprised of the following sections:

- System data section containing information such as number of mobiles and number of sectors;
- Mobile data section, which consists of detail lines containing position, speed, serving sectors, allocated power, etc. for each mobile;
- Sector data section, which consists of detail lines containing position, power, walsh code allocations, etc. for each sector.

At the completion of all drops, the CSSS produces the *Monte Carlo results* file, `MC_cdma_results`, which summarizes, for each sector in each drop, the statistics:

- Total number of mobiles best served;
- Total of the above operating below both FER thresholds;
- Total traffic power allocated by the sector

In addition to these statistics, there is a summary line for each drop which contains the total number of mobiles in the drop and the fraction of mobiles operating below both FER thresholds. From this file, one computes the system outage as the ratio of the number of mobiles operating above either of the FER thresholds to the total number of mobiles in the system.

4 MOBILITY IN CARRIER ASSIGNMENT DISCIPLINES

In this study, we considered only carrier assignment disciplines that assign carriers when the mobile makes its initial access link request. To reassign a carrier during the call requires what is called a *hard handoff*, which can result in brief audio interruption and occasionally a dropped call. Motorola systems reserve hard handoffs for crossing Central Base Site Controller (CBSC) boundaries. Carrier assignment disciplines improve capacity by reducing the variance of some sector resource, such as power or number of mobiles per carrier, at each sector. A sector receives two kinds of link requests, initial access and soft/softer handoff. Since the sector has a choice of carrier assignment for only the initial access link requests, the effectiveness of the carrier assignment discipline is a function of the mix of

these two types. This mix is called the *mobility* of the system, which we will make more precise

The mobility of the system is the ratio of the erlangs consumed by initial access link requests to the erlangs consumed by soft/softer access link requests. A typical mobile (see Figure 1) makes its initial access and N soft/softer handoff link requests at times $T_0, T_1, ..., T_N$, holding each link for periods $\Delta T_0, \Delta T_1, ..., \Delta T_N$. The mobility for such a mobile is

$$m = \frac{E\left(\sum_{k=1}^{N} \Delta T_k\right)}{E(\Delta T_0)}$$

where E is the expectation or averaging operator. If we assume that all ΔT_k are identically distributed and that their common mean is $E(\Delta T_0)$, then, under suitable independence assumptions, it is not difficult to show that
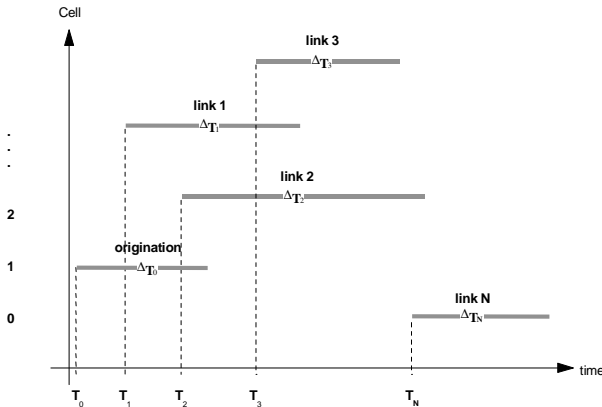

Figure 1: Mobility

$$m = E(N)$$

i.e., that the mobility is the mean number of soft/softer handoff link requests per mobile.

5 MODELING MOBILITY WITH THE CSSS

Since the CSSS does not simulate the complete operation of a mobile from initial access to disconnect, there is no way to infer mobility data. However, it is possible to simulate the phenomenon of mobility without adding the details of adding and dropping soft/softer links. In principle, each CSSS drop generates random variables

$$M = \text{Total \# mobiles in system}$$

$$L_k = \text{\# soft / softer handoff links to mobile } k, \ k = 1, ..., M$$

In an actual CDMA system one could estimate the mobility, *m,* by computing the average ratio of the numbers of soft/softer handoff links and initial access links across a large number of snapshots. In an arbitrary snapshot or drop, we would not expect every mobile to be still connected to its initial access link. To simulate this phenomenon, to each drop we introduce the Bernoulli variables

$$B_k = \begin{cases} 1, & \text{mobile } k \text{ still connected to} \\ & \text{initial access link} \\ 0, & \text{otherwise} \end{cases}$$

where for each $k = 1, ..., M$, B_k equals 1 with probability *p*. We make the further simplifying assumption that for each $k = 1, ..., M$, the B_k are independent of one another and of M.

At each drop we then compute mobility as

$$m = \frac{E(\text{\#soft / softer handoff links})}{E(\text{\# initial access links})}$$

$$= \frac{E\left(\sum_{k=1}^{M}(L_k - B_k)\right)}{E\left(\sum_{k=1}^{M} B_k\right)} = \frac{E\left(\sum_{k=1}^{M} L_k\right)}{p E(M)} \quad (1)$$

Now, the quantity

$$N_L = \frac{E\left(\sum_{k=1}^{M} L_k\right)}{E(M)}$$

is the mean number of soft/softer links per mobile, and is easily computable from the CSSS outputs. Substituting N_L in (1) and solving for *p* we get

$$p = \frac{N_L}{1 + m} \quad (2)$$

Hence, to simulate a CDMA system with mobility *m*, we choose *p* as in equation (2).

6 SIMULATING THE LEAST LOAD DISCIPLINE WITH THE CSSS

The CSSS supports an additional capability which we have not mentioned as yet: Any Monte Carlo statistics file may serve as input (after minor modifications) to the simulator, providing mobile locations, speeds, delay spread, power

class, and other characteristics. The CSSS then re-solves the power control equations for this collection of mobiles. This gives the cellular engineer an opportunity to examine how the system would react to perturbations in a given mobile configuration. This is exactly what is needed to model multicarrier effects with the static CSSS.

Roughly speaking, the procedure for generating a *multicarrier* drop consists of producing a single drop for each carrier, reallocating or "load-balancing" mobiles between those drops in a manner similar to how the least load discipline would work in practice, and then feeding the resulting drops back into the CSSS for estimates of system outage. Figure 2 illustrates the process for two carriers. What we need to make more precise here is the exact nature of the "load-balancing" process.

The first pair of drops in Figure 2 represents how the mobiles would be distributed in a multicarrier system with random carrier assignment. One would expect, on average, that mobiles which are still connected to their initial access links ($\mathbf{B}_k = 1$) are relatively recent arrivals, while other mobiles are relatively earlier arrivals. We assume that one may approximate a typical drop in a multicarrier system $\mathbf{B}_k = 1$ by reassignment of those mobiles k for which, after which one re-solves the power control equation for each carrier. One reassigns the mobiles using the carrier-assignment discipline of the system. (It is tempting to reassign *all* mobiles. However, this would imply all mobiles are still on their initial access links. This would give the system a mobility of N_L, which is incorrect.)
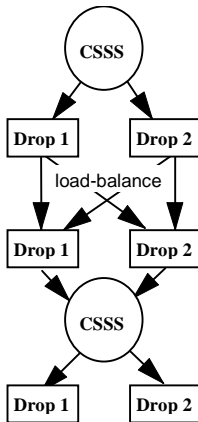

Figure 2: A Multicarrier Drop

A program external to the CSSS performs the reassignment of mobiles, although in the future it will be part of the CSSS. In order to describe the reassignment process in detail, we make the following definitions:
- n = number of carriers
- $d_1,\ldots,d_n$ = input Monte Carlo statistics files

- $d_1^*,\ldots,d_n^*$ = output Monte Carlo statistics files
- Matrix L(s,c) = #links to sector s on carrier c. Initially, L(s,c) = 0 for all s,c

The algorithm for simulating the least load discipline for one multi-drop then proceeds as follows (see Figure 3):

1. Select a detail line at random and without replacement from one of the files $d_1,\ldots,d_n$.
2. Let s = the mobile's best serving sector.
3. Draw a uniformly distributed, random number r from the interval [0,1].
4. If $r < p$, (i.e., $\mathbf{B}_k = 1$) then choose c at random in $\{1,\ldots n\}$ such that $L(s,c)$ has a minimal value. Otherwise, choose c randomly from entire set $\{1,\ldots n\}$.
5. For each sector s' to which the mobile is linked, increment $L(s',c)$.
6. Write the detail line (unmodified) to d_c^*.
7. Repeat 1-6 until the mobile detail lines of $d_1,\ldots,d_n$ are exhausted.

Once this process is completed, the CSSS is run once for each carrier using $d_1^*,\ldots,d_n^*$ as input for carrier 1,...,*n*. This last step is necessary in order to re-establish valid links from mobiles to sectors and to compute outage statistics. We have used the same process to simulate other carrier assignment disciplines, such as least-power, by suitably modifying step 4.

7 SIMULATION RESULTS

Engineers at Motorola have identified model CDMA systems for the purpose of specifying appropriate parameters for actual CDMA systems and estimating their effects. While these models are ideal systems, they are indicative of conditions in interior cells of actual CDMA systems. In order to provide a basis of comparison, we have studied the multicarrier capacities of a subset of these models. We present the results for these models in two types of chart:

- **Comparative Outage Chart** - plots the outage (fraction of mobiles operating above either of the FER thresholds) of the system against the mean number of mobiles per carrier per sector.
- **Comparative Capacity Gain Chart** - plots the capacity gain (per sector per carrier) against outage that a multicarrier system achieves over single carrier system.
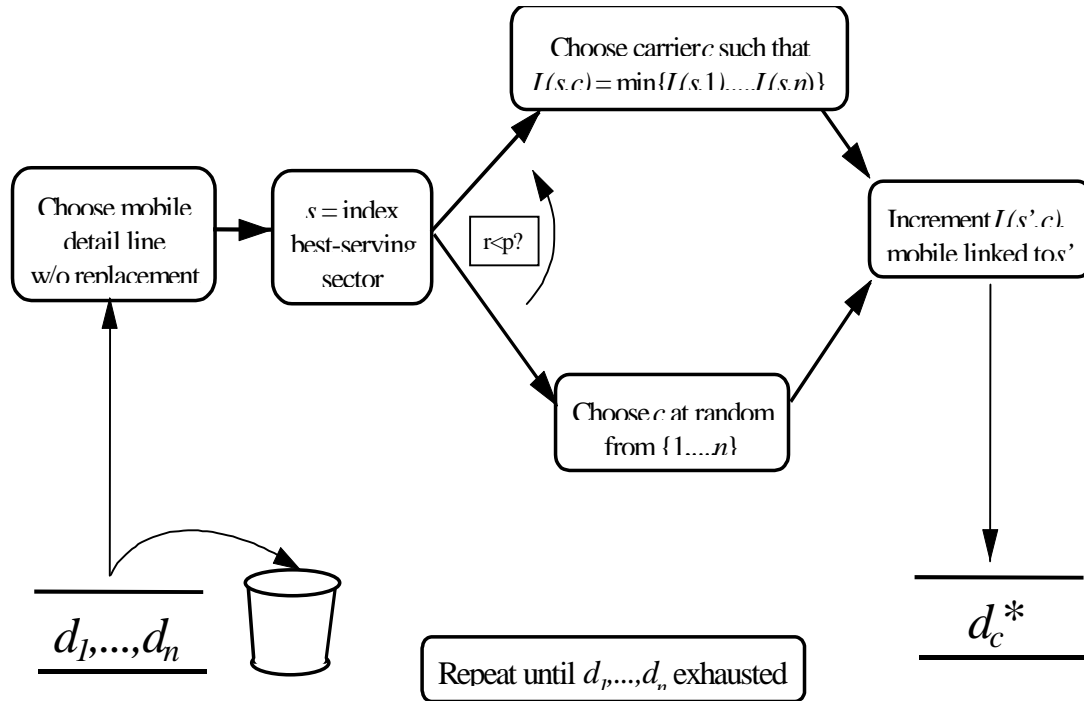
Figure 3: Least Load Algorithm

Each chart presents curves for 1-, 2-, 4-, and 8-carrier systems. Some charts contain additional curves. The reader should be aware that capacity curves show capacities per sector *per carrier*. This means that the actual capacity per sector for an *n*-carrier system is *n* times the capacity read from the capacity curve.

Carrier assignment disciplines tend to be better at improving systems with low per cell capacity. This is analogous to an Erlang B loss system, where capacity improvements are most dramatic when channels are first added to the system. Consequently, all our studies concentrate on 37-cell omni, CDMA rate set 2 systems. Since data applications will be implemented primarily at high bit rates, this concentration is reasonable.

7.1 Mobility=2

If mobility is high, the gain from least load carrier assignment is minimal. This is because base sites spend most of their resources handling soft/softer handoff requests, which can't be carrier assigned. These charts (Figure 4 and Figure 5) show outage and capacity gains for a 37-cell omni system with rate set 2 mobiles and mobility=2. Capacity gains are low with 2 carriers and modest with 4 and 8 carriers.

7.2 Mobility=1

With low mobility, base sites can carrier assign a higher proportion of link requests. Consequently, least load carrier assignment is more effective for the same system with mobility=1. Although capacity gains are still modest for 2 carriers, they are in the 5%-8% range for 4-8 carriers (see Figure 6 and Figure 7).
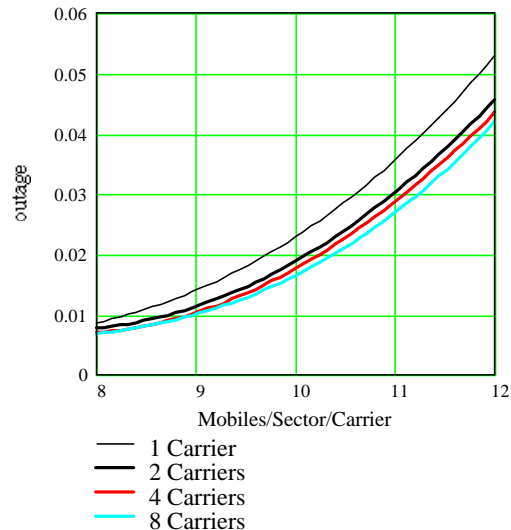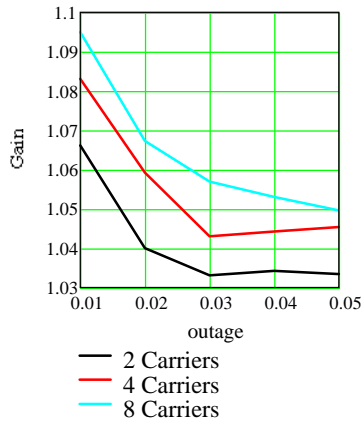
Figure 4: Comparative Outage, Mobility=1

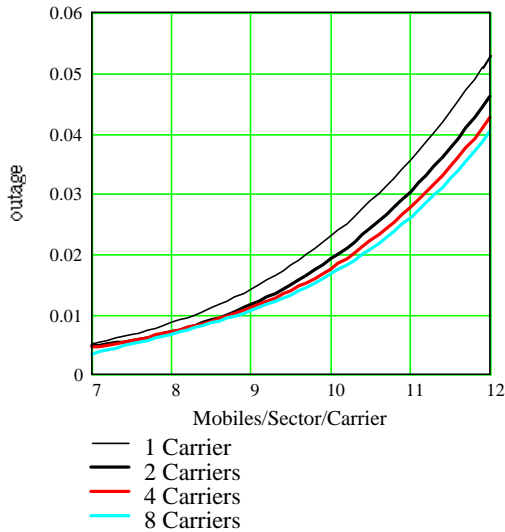Figure 5: Comparative Capacity Gain, Mobility=1
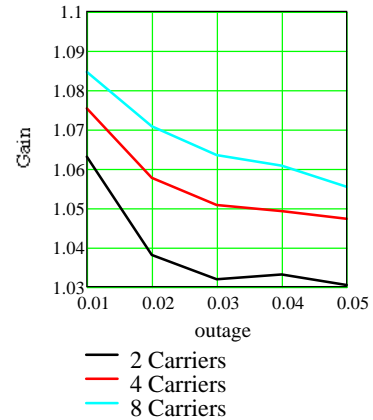
Figure 6: Comparative Outage, Mobility=2

7.3 Mobility=2, High Activity Factor

Even if mobility is high, least load carrier assignment can be effective in recovering capacity in compromised systems. In this system (see Figure 8 and Figure 9), we have mobility=2, but high voice activity rates. This could reflect a high concentration of data users or systems in which ambient audio noise is high. For 4-8 carriers, least load Carrier Assignment can add as much as 10% of additional capacity over Random Carrier Assignment.

8 THE LIMITS OF CARRIER ASSIGNMENT DISCIPLINES

It is certainly plausible that the average capacity achievable in any *n*-carrier system with any carrier assignment discipline is bounded by the capacity of an equivalent *artificial wideband system* (AWS). By this is meant a single carrier system in which the bandwidth is *n* times the bandwidth of the *n*-carrier system, and with *n* times the power for the page,
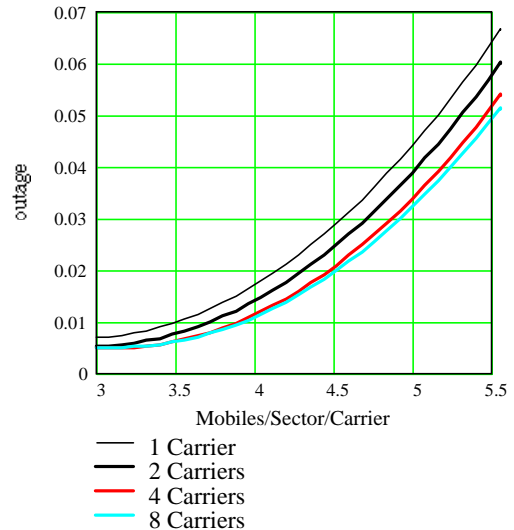

Figure 7: Comparative Capacity Gain, Mobility=2

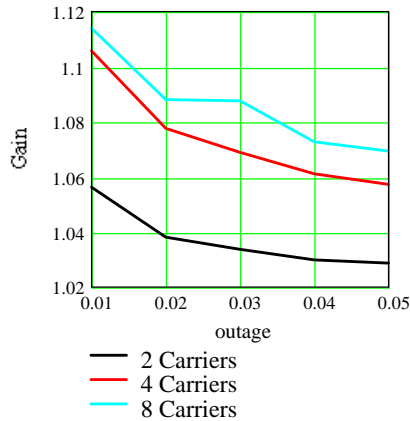Figure 8: Comparative Outage,
Voice Activity=80%

Figure 9: Comparative Capacity Gain,
Voice Activity=80%

pilot, and synch channels. The term *artificial* is used because no one would want to implement such a system, since it is not optimized. It is presented solely for its usefulness in describing the limits of carrier assignment disciplines.

We modified the CSSS to operate with 2, 4, and 8 times the 1.23 MHz bandwidth. The outages from runs with our "wideband" simulator are plotted (see Figure10) in dotted lines together with plots of least load outages for the 37-cell, rate set 2 system with mobility=2. Note that the 2-carrier least load outage curve is more than half way towards the outage curve for the corresponding 2 x 1.23 MHz artificial wideband system. This suggests that more subtle carrier assignment disciplines will not gain much additional capacity.

9   CONCLUSIONS

Simulation studies using the Motorola CDMA Static Simulator with model, omni, CDMA systems have shown that least load carrier assignment can increase the capacity of multicarrier systems. Furthermore, it achieves approximately half the maximum additional capacity achievable by any other carrier assignment discipline.

Least load is most effective in systems with low mobility or with low per sector capacities. Systems with low per sector capacities include those with a large proportion of rate set 2 mobiles or high activity rates, which we will expect to find as data applications proliferate. The proliferation of data applications will also tend to reduce system mobility, which will in turn increase the applicability of least load carrier assignment.
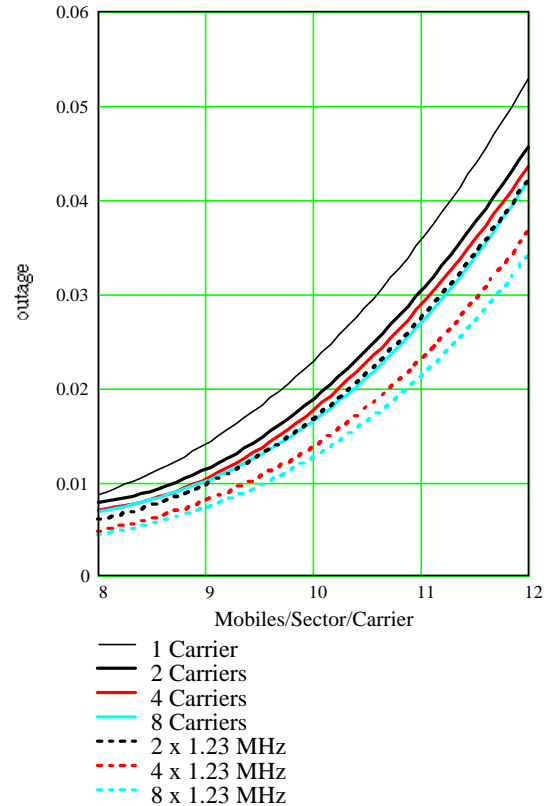

Figure 10: Least Load vs. Artificial Wideband System

ACKNOWLEDGEMENTS

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AUTHOR BIOGRAPHIES

TONY DEAN is a senior staff engineer at Motorola, Inc., where he conducts performance analysis and modeling of cellular infrastructure systems. His research interests lie in the discrete event simulation of such systems. Prior to joining Motorola, he contributed in the development of a patented token-ring based voice and data communications system, engaged in software development for factory data collection terminals, and supported software products at Digital Equipment Corp. and Burroughs Corp. (now Unisys). He holds a Ph.D. degree in mathematical logic from Indiana University.

PHILIP J. FLEMING received his Ph.D. in Mathematics from the University of Michigan in 1981. He spent 10 years at AT&T Bell Laboratories working in the area of computer performance modeling and the last 6 years at Motorola concentrating on the performance analysis of cellular telephony systems. He is the supervisor of the Advanced Cellular Systems Analysis Group at Motorola and his research interests include queueing theory and high speed wireless data networks.

ALEXANDER STOLYAR got his Ph.D. in Mathematics in 1989 from the Institute of Control Sciences, USSR Academy of Science, Moscow. From 1989 to 1991 he was a Research Scientist in the above Institute. He joined Motorola in 1992. His research interests include: stochastic modeling of computer/communication systems/networks, in particular wireless systems; queues, queuing networks, stochastic stability, asymptotic methods.