TRAFFIC MODELING OF A CELLULAR MOBILE RADIO SYSTEM

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ABSTRACT

Cellular mobile radio systems being developed and implemented in North America, Europe and Japan use the frequency reuse concept whereby the same set of frequencies can be used in noncontiguous cells. However, calls in progress may have to be handed off from one RF channel to another as the mobile unit travels across cell boundaries during a call in progress. Further, the operations for setting up, monitoring, coordinating and controlling calls in a cellular mobile radio are radically different from those in a land-based system.

This paper presents the results of a simulation analysis to estimate the performance of the dynamic load-sharing algorithm which is required to ensure negligible probability of call cutoff due to unsuccessful handoffs. It also describes a traffic model to assess the performance of the data link that carries the control messages between the MTX and the cell site controllers.

1. INTRODUCTION

Cellular mobile systems represent the latest technology for providing reliable public mobile telephone service to a large number of customers while providing service quality and features comparable to those of the public switched telephone network (PSTN).

The principle of cellular systems is to divide a large service area into cells with diameters from 2 to 20 kilometers, each of which has a number of radio frequency (RF) channels. Transmitters in adjacent cells operate on different frequencies to avoid interference. However, since the transmitter power in adjacent cells is kept relatively low, cells that are sufficiently far apart can reuse the same set of frequencies.

The coverage range and capacity of the cellular system is potentially unlimited. As the market grows, additional cells can be added and as traffic demand increases in a given area, cells can be split or sectored to accommodate the additional traffic.

The Mobile Telephone Exchange (MTX) in a cellular system allows calls in progress to continue uninterrupted while the mobile moves from one cell to another. The MTX automatically transfers or hands off the call to a different free channel in the adjacent receiving cell.

The operations for setting up, monitoring, coordinating and controlling calls in a cellular mobile systems are radically different from those in a land-based system. In addition, innovative algorithms for dynamic load-sharing between adjacent cells are needed to ensure negligible probability of call cutoff due to unsuccessful handoff.

To meet all these requirements, the MTX must have a high degree of intelligence, design sophistication, and reliability. DMS-MTX®, a cellular mobile system with these characteristics is described in [1] and [2], and its basic architecture is illustrated in Fig. 1.

The traffic parameters that have bearing on the performance and design of a cellular mobile system include:

- blocking on the RF channels,
- blocking on the cellular-to-PSTN circuits,
- probability of a call encountering unsuccessful handoff,
- throughput and delay associated with the data link, and
- call setup delays between the MTX and mobile units.

The blocking performance of the RF channels and the PSTN-connecting trunks can be modelled using classical traffic models [3]. The performance with respect to the remaining three performance parameters for the DMS-MTX system was investigated in detail using computer simulation models and/or analytical models.

In this paper, we present the results on the handoff performance in the presence of the unique dynamic load-sharing strategy implemented in the DMS-MTX system. We also describe a traffic model and provide results on the delay and throughput performance of the high-level data link control HDLC data link that carries the control messages between the MTX and the cell site controllers.

The next section provides a brief description of the dynamic load-sharing algorithm and the cellular system traffic simulator used for assessing the handoff performance. Results on

DMS-MTX is a Trade Mark of Northern Telecom Ltd.
the sensitivity of handoff performance to traffic and system parameters are also presented.

Section 3 describes the traffic models used for the HDLC data link and provides results on the throughput and transfer times.

Conclusions of the analysis are summarized in Section 4.

Fig. 1 DMS-MTX cellular mobile radio system

2. Dynamic Load-Sharing Algorithm and Handoff Performance

2.1 Introduction

One of the unique characteristics of cellular mobile radio systems is their ability to hand off calls in progress between cells. In the DMS-MTX system, when a mobile user moves out from a cell site, he will reach a signal level which has been selected as the beginning of the handoff area. This level is called the RSSI (Received Signal Strength Indicator) and it is used to indicate when a mobile user is a potential candidate for handoff. When conditions are suitable, the call will be transferred from one cell to the next. Call handoff will be more frequent in mature systems where cell sizes may be quite small.

To avoid blocking or loss of calls during handoff, DMS-MTX gives priority to calls requiring handoff. This is achieved by using the dynamic load-sharing algorithms (directed retry and directed handoff) which reserve a given number of voice channels for calls being handed off into the cell.

2.2 The Handoff Algorithm

As we mentioned before, a key feature of cellular systems is the ability to handoff a mobile unit from one cell to another during a call in progress. Basically there are two reasons why a call is handed off: the RSSI from the mobile unit is becoming too weak to maintain satisfactory service; or the traffic load must be balanced among the adjacent cells. The handoff algorithm consists of two parts:

- computing which cells are to receive the request for RSSI message, i.e., which cells are potential candidates for receiving the call being handed off, and
- ranking the responses of these cells from best to worst.

In order to perform these tasks, the handoff process determines in which of the following four states the cell is:

- Normal: origination, terminations and handoff are possible
- Directed Retry: only handoffs into or out of the cell are allowed
- Directed Handoff: only handoff requests due to weak RSSI are accepted. Cell also attempts to handoff calls in progress to the adjacent cells even though they may not be potential candidates for handoff in the 'Normal' state; or
- Unavailable: Cell is either down or has all its channels busy.

To compute which cells are to receive the request for RSSI message, the handoff process obtains the current state of all the adjacent cells. A request for RSSI is sent to cells which are in normal or directed retry state and to directed handoff state only if the reason for the handoff is weak RSSI. The ordering (from best to worst) of the responses (only cells with better RSSI will respond) is done as follows:

- First, normal cells according to RSSI
- Next, directed retry or directed handoff according to channel availability.

Based on the above information, the MTX will choose a suitable cell for handing off the call.

2.3 Dynamic Load-Sharing Algorithm

Dynamic load-sharing algorithms are the means to avoid the blockage of calls or the loss of calls during handoff, and they take advantage of the overlapping cell coverage areas generally designed into a multicell system. This load-sharing is performed on a cell-by-cell basis to help maintain some open voice channels for calls.
requiring handoff due to a weak signal strength. There are two stages in the algorithm for load-sharing:

- Directed retry - routing of calls attempting originations or page responses to a cell site OTHER than the one normally chosen.

- Directed handoff - transfer of some calls in progress to an adjacent cell even though they would not have been handed off under normal state.

If a given cell is in directed retry state and all the adjacent cells are also in directed retry or directed handoff state, the system will respond with a reorder for originations and a release for a page response.

2.4 Cellular System Traffic Simulator

In order to assess the handoff and dynamic load-sharing algorithms, different systems were modelled and studied with the help of the Cellular System Traffic Simulator (CSTS). This computer-aided simulation tool is a comprehensive call-by-call simulator for mobile systems. The simulation’s key parameters are specified by the user through a set of input files. Some of these parameters are: the length of the simulation run, the number of cells and their coverage areas, the average holding time, and the traffic distribution. The cellular system's geographic service area is overlaid with a rectangular grid used in locating the positions of cell site antennas and mobile units with calls currently in progress. The typical statistics collected are: breakdown of call setups according to call type and call disposition; breakdown of calls according to whether they were completed normally, blocked on handoffs or have left the service area; blocking on the RF channels; and the land line trunks, etc. This software tool has been used extensively for analyzing the performance of actual systems during their planning stages.

2.5 The Test System

The results presented in this paper are based on a reference 13-cell mature system. This system is depicted in Fig. 2. It may be considered as an isolated piece of a larger system which has been fragmented for study purposes. The parameters considered in the specification of this system are summarized below:

- Holding times

Cellular mobile radio systems will have relatively short holding times, ranging from 70 s to 140 s. The mean call holding time was set at 120 secs.

- Traffic mix

Normally the Mobile to Land (M-T-L) traffic will be greater than the Land to Mobile (L-T-M) traffic and the Mobile to Mobile (M-T-M) traffic will be relatively low. A distribution of 65% M-T-L, 30% L-T-M and 5% M-T-M traffic was assumed.

- Mobile traffic distribution

This is an important factor for the design of cellular systems. Mobile traffic is usually highly concentrated within certain sectors of a metropolitan area. As an illustration, Fig. 3 is a three-dimensional depiction of mobile traffic density for the reference system studied.

- Contours

They are defined as circles along which the received radio signal strengths are equal to

![Fig. 2 Cell layout (mature system)](image-url)

![Fig. 3 Mobile traffic distribution (Mature system)](image-url)
given signal thresholds. The handoff contour at -85 dBm identifies when a handoff attempt should be initiated. The bad service contour characterizes the minimum RSSI required to maintain adequate service. Mobile units will hit this contour only if they cannot be handed off to another cell in spite of continued attempts by the system to do so.

- **Voice channel grade of service**

The RF channels were dimensioned for 2% blocking under normal load and no dynamic load-sharing. The number of RF channels in each cell is presented in Fig. 2.

- **Cell coverage**

For cellular applications, the coverage is defined as the location of the handoff contour. It is assumed that the small cells have handoff radii equal to 2 km, the medium ones have handoff radii equal to 3.2 km and the large cells have handoff radii equal to 5 km.

- **Cell overlapping**

This is a very important factor for handoff reliability because a layout with a small amount of overlap has less flexibility in handling shifts in mobile user density. The classic hexagonal minimum coverage layout results in only 5.7% overlap between any two cells if the hexagons are replaced by circles. This amount of overlap is not enough for reliable handoffs. On the other hand, excessive overlap may have negative cochannel interference effects, not to mention the extra cost of either increased transmitter power or antenna height.

- **Mobile user speed**

Mobile units are assumed to have Gaussian distributed speeds with means that vary according to specific sectors of the metropolitan area. Mobile units are assumed to travel in the small cell (cell number 1) with an average speed of 30 km/hr with a standard deviation of 20 km/hr. In the system periphery, mobile units have an average speed of 90 km/hr with standard deviation of 30 km/hr.

### 2.6 Results

The improvement in handoff performance provided by the dynamic load-sharing algorithm is illustrated by Fig. 4 where the probability of a subscriber receiving unsatisfactory handoff service (RSSI below -97 dBm) is shown against % overload in traffic. Similarly, Fig. 5 represents the overall blocking perceived by the subscribers as a function of percent overload. Again one can observe that the dynamic load-sharing algorithm provides lower blocking and results in a 10 - 20% increase in traffic handling capacity.

The effect of reserving RF channels is illustrated in Fig. 6 where the following parameters are plotted against the number of RF channels reserved for handoffs:
number of first choice trunks (increase in reserved RF channels), the blocking on the first route increases but the overall blocking is much lower. As the number of reserved channels increases, the blocking of calls within a cell increases. However, the overall system blocking curve exhibits a minimum so that the number of reserved channels can be chosen to minimize the overall system blocking. The probability that a handoff attempt coming into a cell will have to wait for a free channel decreases with the increase in number of reserved channels.

3. HDLC DATA LINK PERFORMANCE

3.1 Introduction

A high-capacity cellular mobile system, such as DMS-MTX, requires a sophisticated centralized control to coordinate the actions of the switching network, the cell site controllers (CSC) and the mobile units. This coordination is accomplished via a data transmission path, which is established between the MTX and the mobile unit. This path consists of dedicated high-level data link control (HDLC) links between the MTX and the CSCs and the radio data channel from the CSCs to the mobile units. Characteristics of the HDLC procedure may be found in [4].

In this section we describe the traffic model to assess the performance of the HDLC protocol under asynchronous balanced response mode (ABR). Two effects may impact performance: sequence-number starvation and error-recovery procedures. Transfer time of messages and throughput are the two primary performance criteria of the link. We follow the analysis presented in [5] to obtain estimates of the link throughput and the transfer time of messages. These two parameters are considered in the specification of the data link so that a uniform and satisfactory overall performance is attained.

3.2 HDLC Traffic Model

A schematic representation of the model underlying the performance of the data link is shown in Fig. 7. Messages to be transmitted from HDLC CSC to HDLC IOC (input/output controller) or vice versa, are stored in the send buffer of the sending station, where they have to wait for transmission. The following assumptions are considered in the model:

- full-duplex point-to-point link connecting the MTX and each CSC
- channel produces statistically independent bit errors with probability BER;
- Poisson arrival process of rates \( \lambda_1 \) (CSC) and \( \lambda_2 \) (MTX);
- fixed-length information frames (I-frames) and
- no processor/buffer limitations.

\[
E[T] = \frac{\lambda [E[T_0]]}{2(1 - \lambda E[T_0])} + E[T_0] + t_1
\]

where \( E[T_0] \) and \( E[T_1] \) denote the first two moments of the virtual transmission time and accounts for the processing as well as the propagation times. Since \( \rho = \lambda T_0 \), while the bit error probability is equal to zero, the expression (1) becomes the M/D/1 formula.
The maximum information throughput (bits/unit of time) of the data link is given by

\[ H = \frac{\rho E[T_x]}{2(1 - \rho)} + E[T_x] + t_x \]  

(2)

The maximum information throughput (bits/unit of time) of the data link is given by

\[ H = \frac{L}{T_0} \]

where \( L \) is the average length of a message.

In our specific case, the modulus is equal to 8, the bit error probability is \( 10^{-6} \), the processing time is 50 ms and it is assumed that the message length is 200 bits.

3.3 Messages Carried By The HDLC Data Link

The following types of messages travel between the MTX and the CSCs:

- Load Messages

They are exchanged for downloading programs and data from the MTX to the CSC over the data link.

- System Maintenance Messages

These messages are exchanged between the MTX and the CSC for conducting diagnostics, maintenance functions, and for reporting or querying of alarm conditions at the CSC.

- Man/Machine Messages

These messages are exchanged for testing and querying the status of the HDLC controllers, etc.

- Operational Measurements Messages

Each Operational Measurements record contains a given number of messages. They are normally collected for statistical purposes.

- Call Processing Messages

These messages serve as instructions to the CSC mobile for originations, terminations, or handoffs.

All these messages have different lengths and also different generation rates. For instance, the loading messages do not normally contribute to the loading of the link since they are exchanged during low traffic hours. The call processing message traffic is a function of the number of cells in the system, as well as the number of adjacent cells for handoff purposes. The first one is due to the fact that for land-to-mobile calls, the MTX does not know the location of the mobiles and it pages all the cells.
cells is caused by the fact that for a land-to-mobile call it is assumed that all the cells in the system are paged to locate the mobile. If the paging is done on zone basis, this effect will be eliminated. If the percentage of land-to-mobile calls increases, this effect will become more noticeable.

Fig. 10 provides results on the effect of system size and traffic loading on message transfer times.

![Graph showing mean transfer time vs number of cells](image)

5. REFERENCES


4. SUMMARY AND CONCLUSION

In this paper we initially introduced the performance analysis of the dynamic load-sharing algorithm for DMS-MTX. This was investigated using a comprehensive call-by-call simulation tool for cellular mobile systems. Some representative results have been presented for a theoretical, mature system. These results indicate that the load-sharing algorithm makes the system behave as an alternative routing or progressive grading system. We found that the load-sharing algorithm increases the effective capacity of the system by 10% to 20%.

Finally we described the performance of the HDLC data link which carries the control information between the switch and the cell site peripherals. Representative results of the message transfer delay as well as occupancies have been presented.