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Traffic Analysis of a Mobile Communication System Based on a Scale-Free User Network

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Abstract—In the traditional study of mobile cellular systems, all users are assumed to have the same behaviour. They have the same probability of making/receiving a call and they will move around the network with identical mobility. Moreover, the underlying user network is assumed to be fully connected. In a practical environment, each user has a different list of acquaintances including relatives, friends and colleagues, with whom the user will make contact. Also, the size of the list varies with individual users. In addition, depending on various factors such as job nature, different users will acquire different levels of mobility. To evaluate the performance of a mobile cellular system more realistically in this paper, we model the user network with a scale-free network in which the number of acquaintances of a user follows a power-law distribution.

1. Introduction

In analyzing the traffic of a telecommunication system in a conventional way, all users are assumed to have identical behaviour. With this assumption, the system can be wholly characterized by the distributions of call arrivals and call holding times, and the number of channels available. Based on such information, the quality of service (blocking probability) of the system can then be easily estimated. However, the equality among users is questionable because in real life, some people will have more acquaintances including relatives, friends and colleagues. These people are thus more likely to make/receive calls compared to those having less acquaintances.

In a recent report involving the study on the long distance telephone calls, it was found that a few callers/callees make/receive a very large number of calls while a large number of callers/callees make/receive very few calls [1]. The investigation further shown that the number of callers/callees and the number of calls made/received follows a power-law distribution. In other words, the user equality assumed in the traditional traffic analysis is violated. A more appropriate model for the user network is found to be a *scale-free* model [2].

In another communication, the authors have already made use of the scale-free model in modeling the user network of a fixed telephone system [3]. Results have indicated that the telephone traffic is highly influenced by the user network behaviour which limits the carried traffic. In this paper, a similar scale-free model will be applied to model the user network of a mobile cellular system. In a mobile system, the geographical area is divided into smaller areas called *cells*. Each cell will be given a number of channels to serve the users within its coverage area. Unlike fixed telephone users, mobile users are not stationary, but move from one cell to another. When a mobile user moves from one cell to another, he will be assigned a new channel by the new cell while releasing the original channel used in the current serving cell. Such a process is termed *handoff*. However, if no free channel is available in the new cell during handoff, the ongoing call will be forced to terminate. In the past, users are assumed to move freely among cells with identical mobility. In practice, different users may acquire different levels of mobility for various reasons such as job nature. Hence, we perform an additional study here in which the mobility of users is assumed to follow a power-law distribution.

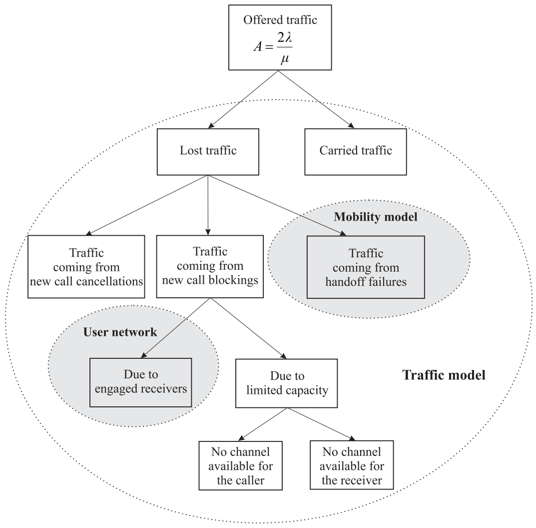


Figure 1: Categories of the offered traffic.

2. Traffic model

In a mobile cellular system, new calls are being initiated randomly according to a certain distribution. Each new call will involve a calling party and a receiving party. When the new call is established successfully, a pair of channels will be occupied and both the caller and the receiver will contribute the same amount of traffic to the system.

Define λ as the arrival rate of new calls. The intensity of the offered traffic, i.e., the total traffic generated by all call arrival attempts, which is denoted by A, can thus be calculated from $A = \frac{2\lambda}{\mu}$,where μ is the call departure rate [4].

In Fig. 1, a detailed categorization of the offered traffic is depicted. Among the offered traffic, part of it has been carried by the network successfully. This portion of traffic is termed *carried traffic*. The rest belongs to *lost traffic*, which is caused by *new call cancellations*, [1] *new call blockings* and *handoff failures*. The

[1]If a user intends to initiate a call when he is already engaged in a

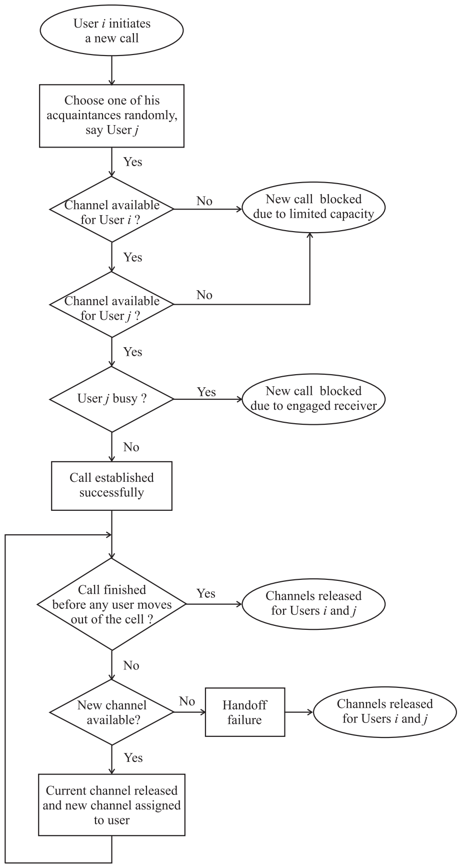


Figure 2: Flow of a call.

new call blockings can be further divided into those due to *engaged receivers* and those caused by *limited channel capacity*. In particular, the blockings caused by engaged receivers are closely related to the user network configuration. On the other hand, the handoff failures are dependent on the user mobility. Thus, both the user network model and the mobility model have an influence on the performance of the mobile cellular system.

Suppose User i wants to initiate a new call. Figure 2 illustrates the flow of the initiation process and the subsequent handling of the call. First, User i randomly chooses a user from his acquaintance list with equal probability. Assume that User j has been selected. If there is no channel available for either user, the call is blocked due to limited capacity. When channels are available for both users, the status of User j will be checked. If he is engaged, the call will be blocked due to an engaged receiver. Otherwise, the new call will be established successfully. When the call is in progress, the mobility of the users is under close monitoring. Whenever a user moves out of the original cell into a new cell, the availability of a free channel in the new cell will be checked. Suppose there is no free channel available, the ongoing call will be terminated due to a handoff failure. Otherwise, the user will release the channel of the serving cell and occupy a new channel of the new cell. The monitoring process will continue until the call is terminated either because the call is completed or a handoff has failed. In either case, the channels being occupied by users will be released.

conversation, the call initiation will not proceed. Such a call blocking is termed as *new call cancellation*.

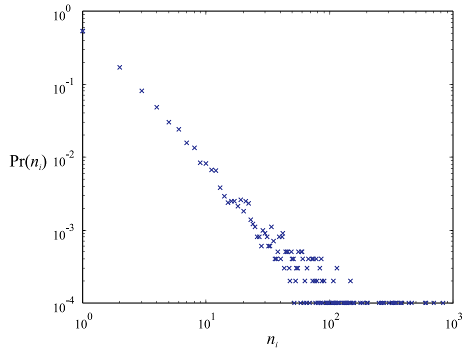


Figure 3: The power-law probability distribution. $\overline{n} = 5$ and $\gamma = 2.1$.

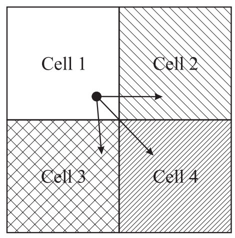


Figure 4: A mobile cellular system with 4 cells.

3. User Network

In our study, a complex network will be used to model the underlying user network of the mobile system. A typical complex network is composed of nodes together with the connections (links) between them [2]. For the user network, each user is represented by a node and a connection is established between two nodes if the corresponding users are acquaintances (such as relatives, friends and colleagues) of each other.

Denoting the number of acquaintances for User i by n_i. The requirement for the *scale-free network* is that n_i follows a power-law distribution, i.e., $\Pr(n_i) \sim n_i^{-\gamma}$,where $\gamma > 0$ is a scaling exponent. The value of γ determines the slope of the probability function and hence the average number of connections per node. Figure 3 shows the probability distribution of n_i of a scale-free user network. From this graph, we can observe that the majority of the users have a few acquaintances, whereas a small number of users (sometimes referred to as *super users*) have a number large of acquaintances.

4. Mobility Model

Consider a mobile cellular system with N users located in M cells. We assume that the cells are adjacent to one another and the cell pattern is shown in Fig. 4 for the case $M = 4$.

To start, users are assigned to the cells equally, i.e., each cell will be given N/M users. Then, the users will be allowed to move freely among the cells depending on their mobility. When a user moves out of the current serving cell, he will randomly choose one of the other cells to move into. For example, a user staying in Cell 1 can move to Cell 2, Cell 3, or Cell 4 with equal probability. Thus, the number of users in each cell at a particular time instant may not be exactly N/M.

5. Results and Discussions

We denote the parameters of the mobile cellular system by the following symbols.

1. λ_i: average new call arrival rate for the ith user;
2. $\overline{\lambda} = \frac{1}{N}\sum_{i=1}^{N}\lambda_i$: average new call arrival rate averaged over all users, where N is the total number of users in the system;
3. $1/\mu$: average call holding time, which is the average call duration between the start time and the end time of a call;
4. $1/\theta_i$: average cell residence time for the ith user, or equivalently, the average time duration during which User i stays in the same cell;
5. c_l: the capacity (number of channels) of the lth cell.

We also make the following assumptions in our study.

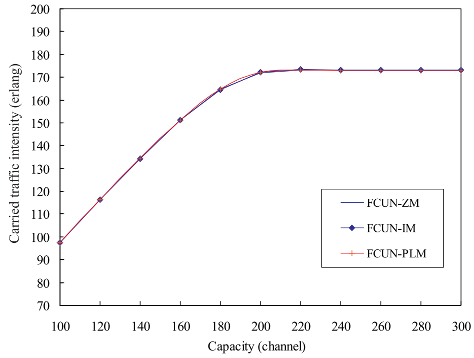
1. The intercall arrival time t for the ith user follows an exponential distribution with mean $1/\lambda_i$ [1, 3, 4], i.e., $f(t) = \lambda_i e^{-\lambda_i t}$,where $f(.)$ represents the probability density function (pdf). We assume that a user with a large number of acquaintances has a higher chance of making an outgoing call or receiving an incoming call. The new call arrival rate of the i user is thus take to be proportional to the number of acquaintances, i.e., $\lambda_i = \alpha n_i$, where $\alpha > 0$ is a proportionality constant that will determine the average new call arrival rate for all users.

   For a scale-free user network (SFUN), different users may have different numbers of acquaintances and hence λ_i may differ between users. For a fully-connected user network (FCUN), since all users are acquaintances of one another, the average call arrival rate will be identical for every user.

   In our study, $N = 10,000$ users are arbitrarily assigned to $M = 4$ cells, with each cell containing 2,500 users before the simulation starts. Also, the average number of acquaintances of a user in the scale-free user network is assumed to be 5, i.e., $\overline{n} = 5$, and $\alpha = 1/500$ call/minute/acquaintance. To ensure a fair comparison between the performance of mobile systems with different underlying user network configurations, the systems will be studied with identical $\overline{\lambda}$, which equals 0.01 call/minute.

2. The distribution of the call holding time t_c is the same for all users. The random variable t_c is exponentially distributed and its pdf is given by $f(t_c) = \mu e^{-\mu t_c}$,where the mean holding time $1/\mu$ is taken to be 4 minutes in our simulations. The maximum offered traffic intensity for each cell is thus approximately equal to $A = \frac{2\overline{\lambda}N}{\mu M} = 200$ E.

3. The time that a user stays in the same cell (called *cell residence time* and denoted by t_m) will determine the mobility of the user. The smaller the cell residence time, the higher the mobility. We assume that t_m for the ith user is exponentially distributed with mean $1/\theta_i$ [5]. The pdf of t_m thus equals $f(t_m) = \theta_i e^{-\theta_i t_m}$.Three different mobility models will be studied. In the first model, users are assumed to be stationary, i.e., they have zero mobility (ZM). This is equivalent to the study of a fixed telephone system [3]. In the second case, all users will assume identical mobility (IM), i.e., $\theta_i = \frac{1}{N}\sum_{i=1}^{N}\theta_i = \overline{\theta}$, $i = 1, \cdots, N$. For the final mobility model, we consider that a large number of users (e.g., people working in an office) stay in the serving cell for a long period of time, while a small number of users (e.g., people on the bus or train) move from cell to cell frequently. In this model, the value of θ_i is assumed to obey power-law distribution, i.e., $f(\theta_i) \sim \theta_i^{-\nu}$,where $\nu > 0$ is a scaling exponent. For the cases of identical mobility (IM) and power-law mobility (PLM), the same average value of θ will be used, which is $\overline{\theta} = 1/120$ minute.



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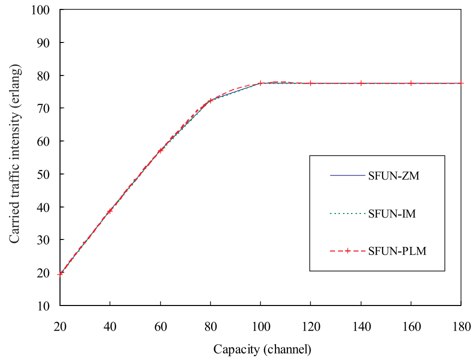


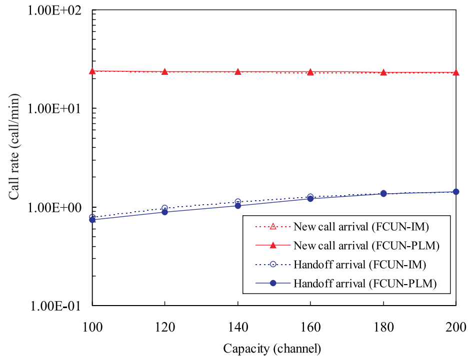
(b)

Figure 5: Carried traffic intensity versus capacity. (a) FCUN-ZM, FCUN-IM and FCUN-PLM; (b) SFUN-ZM, SFUN-IM and SFUN-PLM.

We also assume the numbers of channels assigned to each cell are the same, i.e. $c_1 = c_2, \cdots, c_M$.

Figure 5 plots the carried traffic intensity versus capacity of each cell for the fully-connected user network (FCUN) and scale-free user network (SFUN) under three mobility models. The graphs show that the carried traffic increases with channel capacity up to a certain threshold, beyond which the carried traffic remains constant. It is found that the carried traffic intensity for the FCUN achieves 173 E at a threshold capacity of 200 channels. For the SFUN, it only reaches 77.5 E at a threshold of 100 channels. The threshold values indicate the requirement on the channel capacity and are useful for planning resources in the cells. Also, it can be observed that the mobility model has little effect on the carried traffic.

Figure 6 plots the new call and handoff call arrival rates versus capacity for the FCUN and the SFUN with IM and PLM models. For each user network, it can be observed that IM and PLM models produce similar new call arrival rates and handoff call arrival rates. Comparing the results for the FCUN and the SFUN, the new call arrival rate for the SFUN is lower. For the SFUN, new calls are mainly generated by super users. However, the super users have a high probability of being involved in incoming calls



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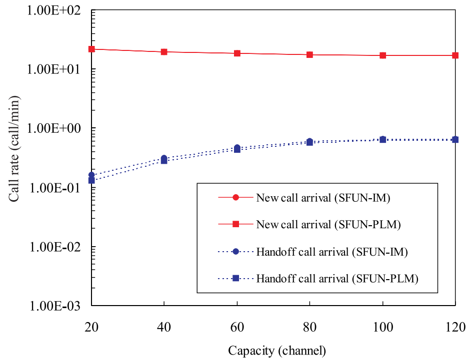
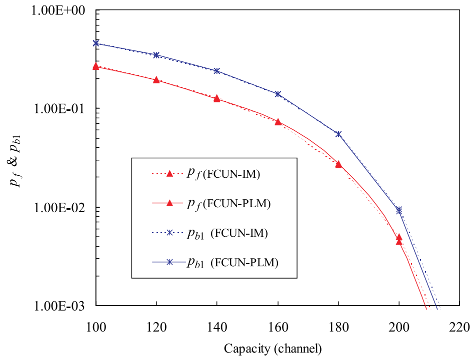


(b)

Figure 6: New call arrival rate and handoff call arrival rate versus capacity. (a) FCUN-IM and FCUN-PLM; (b) SFUN-IM and SFUN-PLM.



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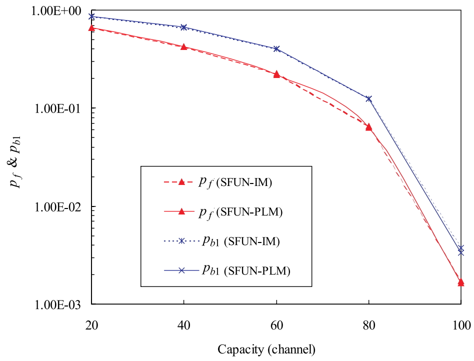

(b)

Figure 7: Handoff failure probability (p_f) and new call blocking probability due to limited capacity (p_{b1}) versus capacity. (a) FCUN-IM and FCUN-PLM; (b) SFUN-IM and SFUN-PLM.

because of the large number of users they are acquainted with. Many of the outgoing calls scheduled to be generated by the super users are thus cancelled, lowering the overall new call arrival rate. For the FCUN, calls are generated evenly among all users and each user has a relatively small probability of being engaged. Thus, more new call arrivals are being produced. Also, because the mobile system corresponding to FCUN carries more traffic, more handoffs are being created compared to the one corresponding to the SFUN.

In Fig. 7, the handoff failure probability p_f and the new call blocking probability due to limited capacity p_{b1} are plotted. It is observed that the handoff failure probability is always lower than the new call blocking probability due to limited capacity. It is easy to understand because the success rate of requesting two free channels (in setting up a new call) is lower than that of requesting one free channel (in handoff). When the number of channels increases, both p_{b1} and p_f are reduced and the difference between p_{b1} and p_f becomes smaller. When the capacity is sufficiently high, both p_{b1} and p_f will become zero. Results also show that IM and PLM models produce similar handoff failure and new call blocking probabilities for each user network configuration. Apparently, it is because of the same average cell residence time being used in the two mobility models.

6. Conclusions

In this paper, we study the performance of a mobile cellular system based on two different user network configurations, namely fully-connected user network (FCUN) and scale-free user network (SFUN). In addition, the mobile system has been simulated under three different mobility models, namely zero mobility (ZM), identical mobility (IM) and power-law-distributed mobility (PLM). Results indicate that the user model produces a very large impact on the performance of the mobile cellular system. When users are allowed to move freely in the mobile cellular system, the mobility of users does not produce a large influence on the overall performance of the mobile system. Based on our findings, mobile operator will be able to deploy more effective channel allocation strategies to further optimize the performance of the mobile cellular systems.

7. Acknowledgments

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