Analytical Survivability Model for Fault Tolerant Cellular Networks Supporting Multiple Services

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Abstract

Survivability analysis measure the degree of functionality remaining in a system after failures. It consists of evaluating metrics which quantify the system performance during failure scenarios as well as in normal operation. Existing research work in this area discusses fault tolerant architecture of cellular networks and analyze impact of failures on the network performance through simulation models. In order to quantitatively assess the effect of failures on cellular networks, we develop analytical model to determine performance oriented survivability metrics in terms of call blocking probabilities. Assuming Markovian property for the networks, these measures are obtained on solving the proposed Markov model. Numerical results are provided for illustration of the proposed model and determination of survivability attributes as mentioned in definition of network survivability performance group.

1 Introduction

Cellular networks for third generation and beyond will support multiple services, for example, voice, data, e-mail, file transfer, live programs and video telephony, with guaranteed quality of service (QoS) requirements. Input traffic from these services is categorized as real time service (RTS) traffic (e.g., voice, video telephony and live programs) and non real time services (NRTS) traffic (e.g., e-mail, SMS). Scarcce radio resources available at cellular networks limit not only the service offering but also QoS. Service degradation is caused by the component failures, software faults, technical faults, malicious attacks and natural disasters, for example, ground shaking, earthquakes, storms and floods [1]. Therefore, fault tolerance is incorporated in cellular networks with motive of mitigating the impact of failures. It is a challenge to provide an acceptable level of service continuity for a set of failure scenarios in an efficient manner. Survivability analysis measures the degree of functionality remaining in a system after failures. It consists of evaluating metrics which quantify the system performance during failure scenarios as well as in normal operation. The results of survivability analysis are typically used to guide network design and protocol development in order to provide fault tolerance.

In the literature, many network technologies have been proposed and survivability performance is analyzed for wired networks including public switched telephone networks, ATM based high speed networks and SONET rings [2, 3, 4]. Relative research work has been done on survivability issues for cellular networks. In [5], survivable architecture for cellular networks consisting of three layers is proposed. The three layers are termed access, transport and intelligent, with survivable strategies possible at each of the layer. Varshney et al. [6] presented an overview of component failures and their impact on the services provided by the cellular networks. Further, they also discussed architectural changes such as SONET rings, multimode/multifunction devices and overlay networks that can improve network survivability. Reference [7] reported the cellular network functions, components, communication links and performance metrics at each layer of survivability framework. Discrete event simulation model has been developed to study the impact of failure scenarios in cellular networks. Tipper et al. [8], based on study of different failure scenarios through simulation models, concluded that it is important to study transient behavior of the system just after the failures. Reason is the immediate increase in network congestion since prematurely terminated users try to re-establish their calls at the same time. Varshney and Malloy [9, 10] presented a modular approach for simulation oriented study of network survivability. In this approach, wireless infrastructure building block(WIB) consisting of base stations(BS), base station controllers(BSC) and mobile switching centers(MSC), is considered as a modular unit. As an extension to the above work, a wireless network with multiple WIBs having varying number of components and links is considered and failure effects on the performance was evaluated through the simulation model [11]. Integer programming techniques are applied to optimize the network design cost of cellular networks while meeting the network survivability requirements.
shown is the architecture of a BS.

An illustrative example, telecommunication system with failures and repairs is considered. Here, single occurrence of failure and no additional failures happening before its repair has been assumed. We extended the idea to present the analytical survivability model for fault tolerant cellular networks that supports multiple services, such as, voice, file transfer, mail access, and video conferencing. Simultaneous occurrence of failures is included rather than a single failure. Further, post effects of failures such as, increase in failure rates and network congestion have also been considered [8]. Analytical survivability model is proposed as a homogeneous continuous time Markov chain (CTMC) that can be solved to obtain the survivability metrics through the software package SHARPE (Symbolic Hierarchical Automated Reliability and Performance Evaluator) [16].

The paper is organized as follows: architecture of a cellular base station is described in section 2. Further, survivability definition proposed by T1A1.2 network survivability performance group has been given in the same section. In section 3, we discuss the basic model of a cellular base station, pure performance, availability model and then performability model. Finally, survivability model is developed which is based on survivability definition developed in section 2. In section 4, numerical illustration is presented to quantitatively examine the effect of failures on the performance of the cellular base stations. Pointers to further research and conclusions are given in section 5.

2 Basic Architectural Concepts

2.1 Cellular Base Station Architecture

Cellular BS is comprised of four principal components: antennas, transmitters and receivers, BS computer unit, and regular and backup power sources [17]. Figure 1 shows the architecture of a BS.

Antenna is used to transmit and receive electronic signals from mobile terminals and base stations. Transmitters, along with antenna propagates digital signals to the destinations. These signals are received by receivers at the destination. Transmit and receive functions, channel processing, encoding/decoding, spreading and many other functions are performed at computer unit of BS. Power control modifies the transmit power, with information gained from the receiver. All operations of transmitters, receivers, antennas and computer units require a regular supply of electric power from the local power supplier. Back-up batteries are placed to ensure steady power supply. Cellular BSs are connected to BSC through wireless microwave or optical fiber links. If this link is severed, then the BS is effectively out of service.

2.2 Fault Model

The channel resources at a BS are effected by transient/intermittent and permanent failures which are discussed as follows:

- **Transient/intermittent failures**: It includes reduction in signal quality of a channel due to transmission impairments, for instance, attenuation, distortion, noise, multipath and fading. In this situation, BS can generally provide its service continuously without interruptions. However, the system capacity, that is, the number of subscribers that the system can support, decreases.

- **Permanent failures**: BS also experiences hardware component failures, software bugs at computer units, faults in electric circuits, electro-mechanical equipment break down, power outages and loss of links with BSC. These failures are collectively termed permanent failures. When a BS encounters permanent failures, it could not accommodate incoming calls. The fault tolerance such as redundant hardware components, spare links and back up power do not allow for termination of ongoing calls. Natural disasters (e.g., floods, storms, ground shaking and earthquakes) cause partial or complete damage to BS infrastructure. In the wake of natural disasters, permanent failures become more frequent for a partially damaged BS. In addition, network congestion also increases because prematurely terminated users of completely damaged BS attempts to re-establish the calls.

![Figure 1: Base station computing unit architecture](image_url)
2.3 Survivability Definition
Survivability describes the available performance of a system after a failure. Survivability analysis measures the degree of functionality remaining in a system after a failure. It consists of evaluating the metrics which quantify network performance during failure scenarios as well as in normal operation. The definition proposed by T1A1.2 network survivability performance group is mathematically precise enough to quantify network survivability [18].

Definition: Suppose a measure of interest \( M \) has the value \( M_0 \) just before a failure occurs. Survivability behavior can be depicted by the following attributes: \( M_0 \) is the value of \( M \) just after the failure occurs; \( M_r \) is the maximum difference between the value of \( M \) and \( M_0 \) after the failure; \( M_r \) is the restored value of \( M \) after some time \( t_r \); and \( t_R \) is the time for the system to restore the value of \( M_0 \).

This definition depicts the time varying behavior of the system after a failure occurs. In this paper, measure of interest to quantify network survivability is in terms of call blocking probabilities of RTS and NRTS traffic. Expressions for transient blocking probabilities, after the failures, for RTS and NRTS traffic, denoted by \( M_{0R}(t) \) and \( M_{0N}(t) \) respectively, are obtained. We next give the description of the model that captures the cellular BS behavior.

3 Basic Survivability Model
In this section, we present the analytical model to quantify the survivability of the cellular networks. Depending on the available resources, performance oriented survivability metrics are obtained in terms of call blocking probabilities for RTS and NRTS traffic.

We begin with description of basic model of a cellular base station. Performance, availability and then composite performance and availability model are discussed. Finally, survivability model is developed from composite model after truncated it accordingly. Since the definition given in section 2.3 depicts time dependent measure of survivability attributes after the failures, transient solutions are obtained for the same.

3.1 Basic Model
Consider a cellular BS with architecture given in section 2.2. Third generation cellular systems are expected to support multiple services, for example, e-mail, voice, video telephony, live programs, SMS, web access and file transfer. The traffic from these service is classified into two categories: real time service (RTS) traffic (e.g., voice, video telephony and live programs) and non real time service (NRTS) traffic (e.g., email, SMS). Assume that the arrival process for RTS and NRTS traffic are Poisson processes with arrival rates \( \lambda_R \) and \( \lambda_N \) respectively. The call completion times for both type of services is exponentially distributed with parameter \( \mu_1 \).

Also, cell residence time for a mobile terminal is assumed to be exponentially distributed with parameter \( \mu_2 \). Therefore, channel holding times (CHT) for both traffic, defined as minimum of call holding times and cell residence times, is also exponentially distributed with parameter \( \mu = \mu_1 + \mu_2 \).

Consider that a BS has \( N \) channels in its channel pool. Since RTS traffic is delay sensitive and requires guaranteed QoS bounds, small number of channels, \( g(<N) \), are reserved exclusively for RTS traffic. When an idle channel is available and an RTS call arrives, it is accepted otherwise blocked. Similarly, if an arriving NRTS call finds at least \( g + 1 \) channels idle, it is accepted, otherwise rejected. By employing homogeneous continuous time Markov chain (CTMC), this paper aims to develop analytical survivability model for cellular BS.

3.2 Pure Performance Model
Pure performance model do not considers failure and repair behavior of a system. Let \( N(t) \) be the number of busy channels at time \( t \). Then, \{\( N(t), t \geq 0 \)\} is a discrete state continuous time stochastic process and can be modeled as a CTMC since Markov property is satisfied at all time points. State transition diagram is depicted in Figure 2 and state index \( i \) gives the number of busy channels.

Figure 2: Pure Performance Model

Distribution for call arrival process and CHT are discussed in above section 3.1. Let \( \lambda = \lambda_R + \lambda_N \), \( \mu = \mu_1 + \mu_2 \). Let \( x_j \) denote steady state probability of CTMC in state \( j \). Steady state probabilities are then given as

\[
\begin{align*}
x_k &= x_0 \left\{ \frac{1}{N} \right\}^{k-N} \frac{1}{N} \left( \frac{\mu}{N} \right)^{k-N+g} \text{ for } 1 \leq k \leq N - g \\
&\text{and } 1 \leq k \leq N - g + 1 \\
&\text{for } N - g + 1 \leq k \leq N
\end{align*}
\]

where \( x_0 \) can be calculated using the normalization equation \( \sum_{k=0}^{N} x_k = 1 \).

Performance Measures
Let steady state blocking probabilities for RTS and NRTS calls be denoted as \( P_{BR} \) and \( P_{BN} \) respectively, in the pure performance model.

The probability of blocking for RTS calls is given by

\[
P_{BR} = x_N
\]

where \( x_N \) is the steady state probability that all \( N \) channels are busy.
The probability of blocking for NRTS calls is given as

$$P_{BN} = \sum_{k=N-g}^{N} x_k.$$  

Time dependent call blocking probabilities for RTS and NRTS calls can be obtained by solving the following system of difference-differential equations

$$\frac{d}{dt} x(t) = x(t)Q$$  

with the initial conditions $x(0) = [1, 0, \ldots, 0]$ and $Q$ is the generator matrix for the Markov chain given in Figure 2. Transient blocking probabilities for RTS and NRTS calls are then given as

$$P_{BR}(t) = x_N(t)$$  
$$P_{BN}(t) = \sum_{k=N-g}^{N} x_k(t)$$  

where $x_k(t)$ gives the probability of CTMC being in state $k$ at time $t$.

Let $E_{Rloss}(t)$ and $E_{Nloss}(t)$ denote the expected number of RTS and NRTS calls lost until time $t$. Then, it can be easily seen that

$$E_{Rloss}(t) = \int_{0}^{t} \lambda_R P_{BR}(x)dx$$  
$$E_{Nloss}(t) = \int_{0}^{t} \lambda_N P_{BN}(x)dx$$  

where $P_{BR}(x)$ and $P_{BN}(x)$ are substituted from (1) and (2) respectively.

### 3.3 Availability Model

We consider a BS that is subjected to transient and permanent failures as discussed in section 2.2. Time to transient failures and repairs are assumed to be exponentially distributed with rates $\gamma$ and $\tau$ respectively. Let $t$ be the time to permanent failures and repairs are exponentially distributed with parameters $\alpha$ and $\beta$ respectively. Permanent failures may recover completely with probability $(1-p)$ and may not be recovered with probability $(1-p)$. In this case, system comes up in degraded mode after the repair action. The assumptions of exponential failures and repairs are made to keep the mathematical analysis tractable. We expect that non-exponential failure and repairs can also be accommodated in such analysis using approximation techniques such as method of phases. Availability model of a BS is a CTMC and state transition diagram is shown in Figure 3.

State index $i$ represents the number of non-failed (either talking or idle) channels and state $S_i$ corresponds to the state of permanent failure at the BS, with $i$ non-failed channels. A new call (RTS or NRTS) arriving at BS gets connected if a non-failed idle channel is available, otherwise it is blocked. Therefore, states $i \in \{1, 2, \ldots, N\}$, are up states. On the other hand, arriving RTS or NRTS calls could not be connected if no non-failed idle channel is available or BS is in the state of permanent failures. Therefore, state 0 and $S_i$, $i \in \{1, 2, \ldots, N\}$ are considered as down states. Steady state blocking probability of state 0, and $S_i$, $i \in \{1, 2, \ldots, N\}$ can be obtained by solving a system of linear equations corresponding to this CTMC or through the software package SHARPE.

Steady state availability of the BS, denoted as $P_A$, is obtained as the sum of the steady state probabilities of up states $\{1, 2, \ldots, N\}$. Therefore, we get

$$P_A = \sum_{k=1}^{N} \pi_k$$

where $\pi_k$ is the steady state probability of CTMC being in state $k$.

### 3.4 Performability Model

Composite performance and availability model, known as performability model, discusses the performance associated with failure and repair behavior of a system. Performability model for a BS is then, a two dimensional CTMC. Figure 4 shows the state transition diagram, where the parameters have usual meanings.

State $(n,j)$ denotes $n$ non-failed channels with $j \leq n$ ongoing (RTS or NRTS) calls in the system.

$S_{n,j}$ corresponds to state of permanent failure with $n$ non-failed channels and $j$ calls ongoing in the system.

Transition rate from state $(n,j)$ to $(n-1,j)$ is $(n-j)\gamma$. It corresponds to the failure of any one of the $(n-j)$ idle channels. Transition rate from the state $(n,j)$ to the state $(n-1,j-1)$ is $j\gamma$ due to the failure of one of the $j$ channels carrying the calls. Steady state probability $\pi_{k,j}$ can be obtained using SHARPE.

#### Performance measures

Steady state blocking probability for RTS calls is given by

$$P_{BR} = \sum_{k=1}^{N} \sum_{i=0}^{k} \pi_{S_{k,i}} + \sum_{k=0}^{N} \pi_{k,k}$$  

Similarly, steady state blocking probability for NRTS calls is given by

$$P_{BN} = \sum_{k=g+1}^{N} \sum_{i=k-g}^{g} \pi_{k,i} + \sum_{k=0}^{g} \sum_{i=0}^{k} \pi_{k,i} + \sum_{k=1}^{N} \sum_{i=0}^{k} \pi_{S_{k,i}}.$$
Steady state probability $\pi_{k,j}$ will provide for initial probability vector in survivability model presented in the next section. $P_{BR}$ and $P_{BN}$ provide the values of $M_{BR}^N$ and $M_{BN}^N$, call blocking probabilities of RTS and NRTS traffic before the natural disaster occurred.

Figure 4: Composite Performance and Availability Model

### 3.5 Survivability Model

As mentioned in section 2.2, aftermath of malicious attacks and natural disasters induces more frequent permanent failures and increase in network congestion. Whenever a BS encounters permanent failure, it could not provide connections to incoming RTS or NRTS calls. However, ongoing calls are not lost due to fault tolerance introduced at various components of BS. We assume that permanent faults are recovered with coverage probability $p$ or remains uncovered with probability $1 - p$. In this case, these failures are recovered after a graceful degradation of BS wireless resources.

We next construct survivability model from performance model discussed in section 3.3. Definition of survivability in section 2.3 indicates the time-dependent behavior of the system after the failures. Therefore, we determine transient blocking probabilities for RTS and NRTS calls. Suppose we consider the situation after natural disasters have hit a cellular network geographic area. We want to determine performance oriented survivability metrics in terms of call blocking probabilities at a BS that experience the aftermath of natural disasters.

Let BS be in state $(n,j), \{1 \leq n \leq N, 0 \leq j \leq n\}$ at the time of occurrence of natural disaster. To develop analytical model for survivability, from performability model given in Figure 4, the rows corresponding to states with $n$ non failed channels and below it are included. Rows above the state $(n,j)$ are truncated from the composite performability model shown in Figure 4. Also, remove transitions from states $(n,j), 0 \leq j \leq i$, to state $S_{n,j}$ since we want to determine behavior given a disaster has happened. The truncated model of survivability is then modeled as CTMC. Figure 5 shows the state transition diagram for the survivability model. In this model, arrival rates of RTS and NRTS traffic, $\lambda_R$ and $\lambda_N$ are expected to increase due to increase in network congestion. Further, exponential rate of permanent failures also increases as these failures becomes more frequent after natural disaster has occurred in a geographic area. The initial probability assignment

Figure 5: Truncated CTMC for Survivability Model

\[ p_{i,j}(0) \text{ and } p_{S_{i,j}}(0) \text{ of the states in the truncated composite model indicates the probability vector of the system right after the occurrence of the permanent failures. We set } p_{i,j}(0) = 0, 1 \leq i \leq n, 0 \leq j \leq n, \text{ since the permanent failure has already occurred. } p_{S_{i,j}}(0) \text{ is initial probability for the system to be in state } S_{n,j} \text{ and is determined by the probability that system is in state } (n,j) \text{ before the permanent failure happens. Therefore, for fixed state } n, \]

\[ p_{S_{n,j}}(0) = \frac{\pi_{n,j}}{\sum_{k=0}^{n} \pi_{n,k}}, 0 \leq j \leq n \]

\[ p_{i,j}(0) = 0, 1 \leq i \leq n-1, 0 \leq j \leq i \]

and $\sum_{j=0}^{n} \pi_{n,j} = 1$ holds. Here, $\pi_{n,j}$ is steady state probability for state $(n,j)$ in the performability model discussed earlier.

In case, the number of non-failed channels, $n$, is less than the number of guard channels, i.e., $n \leq g$, a
cell is not able to set up NRTS calls because all the available channels are made available for high priority RTS calls. However, if $n > g$, then $g$ channels remain reserved for the RTS calls exclusively and rest of the available $n - g$ channels are shared by both, RTS and NRTS, calls according to the fixed guard channel policy.

Performance oriented survivability metrics
Survivability metrics of cellular BS after natural disasters has occurred are determined in terms of call blocking probabilities of RTS and NRTS calls, denoted by $M^{BR}_a(t)$ and $M^{BN}_a(t)$, respectively.

We now compute the transient blocking probability $M^{BR}_a(t)$ for RTS calls after the wake of a natural disaster in a cellular network service area. At a BS, an incoming RTS call is lost for the following two cases:

- BS is in the state of permanent failures.
- Non-failed idle channels are not available at BS.

Therefore, summing up transient probabilities of the corresponding states, the transient blocking probability $M^{BR}_a(t)$ for RTS calls after natural disaster has occurred is given by

$$M^{BR}_a(t) = \sum_{k=1}^{n} \sum_{i=0}^{k} p_{k,i}(t) + \sum_{k=0}^{n} p_{k,k}(t). \quad (5)$$

where $p_{k,i}(t)$ and $p_{k,k}(t)$ are the transient probabilities of state $(k, i)$ and $(S_{k,k})$ in survivability model shown in Figure 5. Before the natural disaster happens, blocking probability of RTS calls is denoted by $M^{BR}_a(0)$. It is given by steady state blocking probability $P_{BN}$ of NRTS calls obtained in section 3.4, that is, $M^{BR}_a(0) = P_{BN}$, where $P_{BN}$ is given by equation (4). The above measures, $M^{BR}_a$, $M^{BN}_a$, $M^{BR}_a(t)$ and $M^{BN}_a(t)$ are obtained through software package SHARPE.

4 Numerical Results
In this paper, our objective is to present the analytical survivability model for the fault tolerant cellular networks. We next illustrate the applicability of survivability analysis in section 3 through numerical results. The time to permanent and transient failures and repairs are assumed to be exponentially distributed for analytical tractability of survivability analysis. However, survivability analysis can also be carried for non-exponential (general) failure and repair distributions through the approximation techniques.

For the sake of analytical tractability and an illustration to the proposed model, we consider a cellular BS with capacity of four channels out of which 25% are reserved for RT calls, i.e., $N = 4$ and $g = 1$. Further, we assume the coverage probability $\gamma$ for permanent failures as 0.98 and with probability $(1 - \gamma)$, these failures are not recovered completely. In this illustration, BS comes up in a degraded mode after repair. The parameters for exponential distributions of inter arrival time, service time, failure and repair times, along with their description and values, as assumed in this illustration, are given in Table 1. With the parameters assumed in this illustration, the performance oriented survivability measures so obtained can provide the benchmark to the network designers while modeling the real systems. Steady state probabilities of

$$M^{BN}_a(t) = \begin{cases} \sum_{k=g+1}^{n} \sum_{i=k-g}^{k} p_{k,i}(t) + \sum_{k=0}^{g} \sum_{i=0}^{k} p_{k,i}(t) & n > g \\ \sum_{k=1}^{n} \sum_{i=0}^{k} p_{k,i}(t) + \sum_{k=1}^{n} \sum_{i=0}^{k} p_{k,i}(t) & n \leq g \end{cases} \quad (6)$$

where $p_{k,i}(t)$ and $p_{k,k}(t)$ are the transient probabilities of state $(k, i)$ and $(S_{k,k})$ in the truncated model of survivability shown in Figure 5. Before the natural disaster occur, blocking probability of NRTS calls is denoted by $M^{BN}_a$. It is given by steady state blocking probability $P_{BN}$ of NRTS calls obtained in section 3.4, that is, $M^{BN}_a = P_{BN}$, where $P_{BN}$ is given by equation (4). The above measures, $M^{BR}_a$, $M^{BN}_a$, $M^{BR}_a(t)$ and $M^{BN}_a(t)$ are obtained through software package SHARPE.

### Table 1: Model Parameter description and Values

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Meanings</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_N$</td>
<td>Arrival rate of NRTS calls</td>
<td>1</td>
</tr>
<tr>
<td>$\lambda_R$</td>
<td>Arrival rate of RTS calls</td>
<td>2</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Rate of CHT</td>
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</tr>
<tr>
<td>$\gamma$</td>
<td>Transient failure rate</td>
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<tr>
<td>$\tau$</td>
<td>Transient repair rate</td>
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</tr>
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<td>$\alpha$</td>
<td>Permanent failure rate</td>
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<tr>
<td>$\beta$</td>
<td>Permanent repair rate</td>
<td>15</td>
</tr>
</tbody>
</table>
The performability model shown in Figure 4 are obtained through the use of software package SHARPE. Then, blocking probabilities of RTS and NRTS calls are obtained from equations (3) and (4), respectively. Thus, we get

Blocking probability of RTS calls, $P_{BR} = 1.8903 \times 10^{-2}$

Blocking probability of NRTS calls $P_{BN} = 1.572 \times 10^{-1}$

After the disaster has occurred, network congestion increases and permanent failures become more frequent. We suppose that after the failure, RTS and NRTS calls now arrive with rates $3 \text{ sec}^{-1}$ and $2 \text{ sec}^{-1}$ respectively. Also, assume that the rate of permanent failure increases by a factor of 10, that is, rate of permanent failure increases from .00004 to 0.0004. Further, the coverage probability of permanent failure reduces to 0.90. For the sake of illustration and analyzing the scenario of a system after the disasters in a more reasonable way, we assume the above parameters different from the earlier values and keep the other parameters same. We use software package SHARPE to obtain transient blocking probabilities for the survivability model shown in Figure 5. We, then, compute the time dependent blocking probabilities for RTS and NRTS calls using the equations (5) and (6).

![Figure 6: Blocking Probability for RTS Calls Vs Time](image)

Figure 6 shows the variation of blocking probabilities of RTS calls with time. Further, survivability attributes such as $M_0^R$ and $M_a$ as mentioned in the definition of survivability given in section 2.3 are also obtained from the above curve. We observe the drastic increase in the blocking probabilities of RTS calls after the disasters occurs. Similar discussion holds for NRTS calls also. Since after the disaster has occurred, traffic congestion increases, permanent failures becomes frequent, and coverage probability for recovery of permanent failure is reduced, percentage of NRTS calls rejected after the disasters is higher than that of RTS calls.

Thus, the above quantification procedure shows how the analytical survivability model can be developed and survivability oriented performance metrics such as $M_0^{BR}$, $M_0^{BN}$, $M_a^{BR}(t)$ and $M_a^{BN}(t)$ are computed. Numerical results illustrates the above procedure.

### 5 Conclusions

In this paper, we have presented an analytical survivability model to determine the performance of a cellular BS in terms of call blocking probabilities for real time and non-real time service traffic. The analysis carried out in this paper takes into consideration the post-effects of natural disasters such as increase in network congestion and more frequent permanent failures. The numerical illustration shows that the blocking probabilities for RTS and NRTS calls experience a great increase after the disaster has occurred in a geographic service area of cellular network. It is our belief that the proposed model may be of great interest in the design and operation of survivable cellular networks supporting multiple services. We are currently working on developing an analytical model to determine the survivability of cellular networks, considering the failures of base station controllers, mobile switching center and failure of database that supports roaming services and user authentication information.

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### References


