



Reliability and survivability assessment of LTE-A architecture and networks

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Abstract

In the world of broadband network, Long Term Evolution-Advanced (LTE-A) is facing a large demand due to its high-speed wireless data transmission, extensive coverage from base stations, and a luxury of upgrading protocol software. However, its efficiency depends mainly on the two significant attributes which are reliability and survivability. Further, the prospects of these attributes are mainly based on the LTE architecture and network. In this paper, a hierarchical model is developed based on the architecture of LTE-A networks. Stochastic modeling techniques such as continuous time Markov chains and reliability block diagram are used to obtain reliability, availability and survivability metrics. Further, these metrics are analyzed numerically using the hierarchical model.

Keywords LTE-A networks · Reliability · Survivability · Continuous time Markov chain · Reliability block diagram

1 Introduction

The Long term evolution (LTE) is a standard for a high-speed wireless communication of mobile devices and data terminals. Further, LTE-Advanced (LTE-A) is the next major step in the evolution of wireless technology. The purpose of LTE-A is to effectively meet the current generation demands of high speed data rate, spectral

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efficiency, and lower latency [1, 2]. However, factors such as, hardware and/or software failure and power supply outage due to antenna tilt, software bugs, environmental changes, etc., can be the reasons behind network system's¹ inefficiency [3]. In today's scenario basic requirements in LTE-A network, such as, network reliability and survivability mechanism are the need of the hour. Furthermore, these mechanisms need to be evaluated by suitable models for their reliability, availability, and survivability attributes.

Analyzing a complex systems such as LTE-A can be a very difficult task. Accounting for many challenges and issues such as understanding the architecture of the LTE-A, identifying the structure of the network, etc. are the core basic requirements [4, 5]. Though in the past, some survivability models for earlier network system have been presented, but a comprehensive analysis is not available for the same [6–8].

Universal Mobile Telecommunication System (UMTS) is a technology prior to the next generation LTE and LTE-A. In [6], a hierarchical model is presented for UMTS using Reliability Block Diagrams (RBD) and Continuous time Markov Chains (CTMCs). On the similar lines, reliability and survivability analysis of LTE-A networks is presented in this paper. In [9], reliability and survivability analysis of the Vehicular Ad hoc Network (VANET) is conferred. A hierarchical model is developed which is further studied using RBDs and CTMCs. For LTE-A networks, the system level simulation model has been proposed in [10]. Performance of the downlink connection is analyzed using different workloads in LTE-A, [11]. In [12], authors have developed a simulation model for the handover performance in an LTE-A interface to check the interdependence and impact of various handover situations for UE's of different speed. A computationally efficient LTE-A system level simulator using MATLAB is presented for LTE-A networks. To calculate the structural reliability and the reliability index based on the chance theory, a method is proposed, which can be used to handle the problem of mixed uncertainty. The structural reliability is calculated using chance measure and chance distribution [13]. Also, to find the reliability of a system containing motion mechanism is a tedious task. A phenomenon in motion mechanism occurs when the components do not have structural failure and joint failure, but the function of the mechanism cannot meet the requirements. A series system reliability allocation model with three types of failure modes based on the Gumbel Copula was considered [14].

In recent times, the analytical model for the performance analysis of VANET system is presented for LTE mobile communication networks [15]. In [16], architecture based approach is discussed for the reliability assessment of software components². Further it is described how can this be used to examine software behavior right from the design stage to the implementation and to the final deployment. However, the availability of independent components reliability is not discussed in detail. In [8], the survivability of a network with virtual

¹ System is an interdependent group of items forming a unified whole.

² Components are any hardware or software part of the network, such as, any link, base station, a part of base station, etc.

connections, exposed to the link or the node failures is accessed. The transient performance of the virtual connections after an undesired event is obtained. But, multiple failure of components is not considered.

To the best of author's knowledge, in past various analytical models have been proposed to address the problem of quantifying the hardware and software reliability, for a general wireless network, however not specific to the LTE-A networks. Lately, repairable multi-state system which operates under dynamic regimes with discrete time hypothesis is developed by [17]. Reliability measures taken as sojourn times are obtained. In real life scenario, the assumption of the discrete time for any system does not serve the purpose. In this paper, failure, repair, and replacement of the components for the dependability analysis of LTE-A networks are explored. Dependability attributes such as reliability, availability, and survivability for the LTE-A networks are analyzed [18].

The contribution of the manuscript are the following:

- Proposed analytical model is a notably generalizable model and produces results for which a comparison with the state-of-the-art technique is not achievable. It is due to the fact that the purpose of this work is, not to give experimental results and discussion, but to offer the guidelines for providing advanced dependability understanding of the LTE-A networks.
- The importance of several challenges pertaining to Radio Resource Management (RRM) for LTE-A (radio resource utilization, complexity and Quality of Service(QoS)) are highlighted and discussed.
- A comprehensive survey of recently proposed RRM schemes for LTE-A networks is presented. It is examined that how the mechanism of approach used addresses the technical challenges.
- In this work, a novel hierarchical model is presented for the performance analysis of LTE-A networks, which is further classified into the upper level and lower level models. Upper level models are RBDs whereas lower level models are CTMCs. This classification is performed to capture a realistic approach towards modeling because dependent behavior and repair of failed components, etc., are not taken into account by an RBD model.
- Assuming exponential distribution for failure and repair of components, dependability measures are investigated. Also, these measures such as reliability, availability, blocking probability, etc., can be used in providing essential guidelines for the improvement in network designing and QoS of the user. In our future research, we shall compare the existing analytical results, with results obtained from simulated scenario.

The rest of this paper is organized as follows: The general reference architecture of LTE-A network is described in Sect. 3. In Sect. 4, a hierarchical model is discussed. In Sect. 5, an analytical model for evaluating the network availability and survivability is developed. Section 6 presented the numerical analysis of the proposed model. Finally, pointers to conclusions and future work are given in Sect. 6.

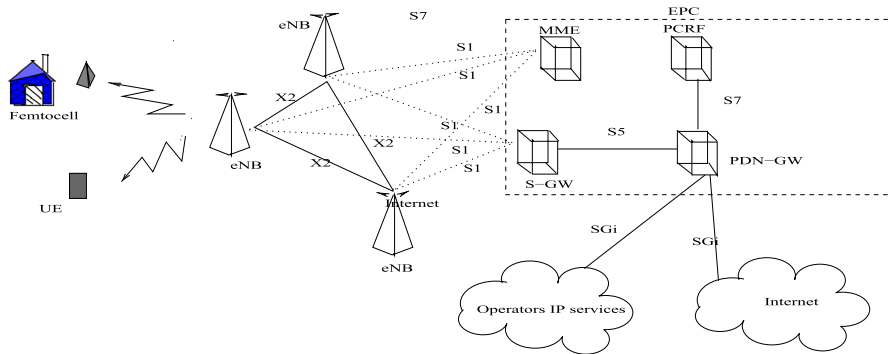


Fig. 1 Architecture of LTE-A networks

2 LTE-A architecture

LTE-A network is an Internet Protocol (IP) based network and therefore is designed, to efficiently support packet-based transmission. Various modules are responsible for transmission of packets in LTE-A networks [1]. In the following subsection, functionalities of the main modules, which compose the basic structure of LTE-A network are discussed.

2.1 Rationale components of LTE-A basic system architecture

LTE-A system architecture is partitioned into two parts: Evolved universal terminal radio access network (E-UTRAN) and Evolved packet core (EPC).

E-UTRAN consists of the following components [19, 20]:

1. *User equipment (UE)* a UE is a device that an end-user uses for communication. It can be a smart phone, data card or a laptop, etc. As a function, UE is a place for communication applications. UE's main work is to maintain and add/remove the communication links, setting up the network according to the end-users need.
2. *Evolved NodeB (eNB)* an eNB is a radio base station that is in the control of all the radio related functions. eNB's are usually distributed all over the network coverage area. As a function, eNB acts as a layer 2 bridge between UE and EPC, by being the termination point of all the radio protocols towards the UE, and relaying data between the radio connection and the corresponding IP based connectivity towards the EPC.

Further, EPC is a mobile core network, and its main responsibilities are mobility management, policy management, and security. It consists of the following components, a depiction of the LTE-A architecture with components have been given in Fig. 1, [21]:

1. *Serving gateway (S-GW)* S-GW is responsible for overall packet routing as well as forwarding to and from the UE. It acts as a local mobility anchor (for inter-eNB's).
2. *Mobile management entity (MME)* it is a control plane node³ which processes the signaling between UE and S-GW.
3. *Home subscriber server (HSS)* HSS contains user's System Architecture Evolution (SAE) subscription data, such as, the EPS-subscribed Quality of Service (QoS) profile and any access restrictions for roaming. Also, it holds information about the Packet Data Networks (PDN) to which the UE can connect.
4. *Packet data network (PDN) gateway (P-GW)* it is a gateway that connects a UE to external packet data networks, such as the Internet and IMS⁴. Also, it is responsible for the IP address allocation for UE. P-GW moderate QoS, as it can control IP packet flow to the UE. The PDN gateway has the same role as the GPRS Support Node (GGSN) and the Serving GPRS Support Node (SGSN) with UMTS and GSM⁵ [20].
5. *Policy control enforcement function (PCRF)* it is responsible for policy control decision-making. In addition, it controls flow-based charging functionalities in the P-GW.

We have modeled the aforementioned architecture using the three approaches, which are, reliability type model, availability type model, and survivability type model. The main reason behind using the three different types of approaches is that, in case of reliability models and availability models, service quality is not covered, whereas, in case of survivability modeling, the analysis is conducted into various class of services. Therefore, practicing this classification of dependability attributes helps in understanding and assessing their impact on the overall network system.

Now, to investigate the architectural based dependability attributes, we discuss the basic approach for the analysis of system [7, 22].

1. *Architecture of the software* software architecture includes the manner in which the different components of the system interact with each other and the outside components of other systems. It also includes the information about the initiation, termination, time spent as well as execution time, etc.
2. *Architecture of the hardware* hardware architecture refers to the identification of a system's physical components and their interrelationships. It only includes the physical connections of the different components of the system.
3. *Failure and repair behavior* it is associated with the architecture of the hardware and software. Failure is possible during an execution period of any functioning of some component or control transfer between two components or between the interface of two modules having the different set of components.

³ Node is either a redistribution point or a communication endpoint.

⁴ IMS stands for IP multimedia subsystem which facilitates the use of IP for packet communications.

⁵ GSM stands for Global System for Mobile communication and is a digital mobile telephony system that is widely used in Europe and other parts of the world.

In this paper, their failure behavior is specified in terms of reliabilities or failure rates. Further, we have assumed that all component failure events are mutually independent. Also, rates of failure and rate of repair of identical components are considered to be same. In addition, failure of identical component can occur due to different reasons.

In the next section, an analytic hierarchical model is developed, in which upper level model is an RBD and Continuous Time Markov Chains (CTMCs) are the lower level models. Upper level model is further classified into reliability and availability at three sublevels, i.e., at level 1, level 2 and level 3, which is discussed in three Sects. 4.2, 4.3 and 4.4, respectively.

Now, before proceeding further, we discuss a question that is, why is this classification required ?

Since, in a reliability models, the repair after individual component failures are admitted, but the repair from a network failure is not taken into account. Thus, a state space type CTMC model with absorbing and without absorbing state should be considered for reliability and availability models, respectively. Also, CTMC enables us to model complicated interactions among the components, and tradeoffs among the different measures of interest. They allow explicit modeling of complex relationships and transition phase of components is encoded with all the sequencing information. Moreover, some features of a system, like, dependent behavior, nonzero reconfiguration delays and imperfect coverage are not captured in a RBD model. Hence, a switch from RBD to CTMC model is performed in moving from the upper to lower level model.

3 Reliability model: at the architecture level

In this section, first, the terms reliability and availability are briefly introduced [23]. Second, some preliminary terms are explained and further LTE-A network system architecture is discussed. Third, reliability and availability are obtained at three different levels.

Reliability: It is a component's or network's ability to perform a designated set of functions under certain conditions for specified operational times.

Further, let T be a random variable representing the time to failure of a component or system. Mathematically, reliability can be expressed as the probability that the time to failure of the component or system is greater than or equal to a specified period of time (t):

$$R(t) = P[T \geq t]$$

To model system reliability, it is required to know about failure behavior of components, i.e., the probability of failure before time, t [21, 24], and how are they interconnected to form the system [25, 26], discusses that the channel holding, failure and repair time distribution fits well with the Exponential distribution.

Availability: It is a component's ability to perform its operations at any given instant under certain conditions.

If we define the status function $X(t)$, where

$$X(t) = \begin{cases} 1, & \text{system functions at time } t \\ 0, & \text{otherwise.} \end{cases}$$

therefore, the availability $A(t)$ at time $t > 0$ is presented by

$$A(t) = \Pr[X(t) = 1] = E[X(t)].$$

To make connections, the S1 interface connects eNB to EPC whereas X2 interface is used in mobility among the eNB's. If an X2 interface exists between the source eNB and the target eNB, then the source eNB sends an X2 : Handover Request message, to target eNB to prepare the target cell. The target eNB builds a Radio Resource Control (RRC) connection reconfiguration message and transfers the Handover Request acknowledge message to source eNB in the X2 interface.

Now, before proceeding further for the modeling section, we discuss some preliminaries terms which are required to understand.

3.1 Preliminaries

1. *Handover* it is a process of connection interaction exchanges between the UE and the network, when UE roams.
2. *Link fault* it is a most common reason for a handover failure from source eNB to target eNB. It is a physical sync issue, as target eNB does not have resources for handover bearers. Also, Radio Link Failure (RLF) happens, when target eNB do not receive the respond.
3. *Power fault* power faults are mainly caused due to limited battery life. Moreover, it occurs due to excessive work load on an eNB which leads to its battery consumption.
4. *Component failure* when a component produces incorrect output or no output, then it is called component failure. It may happen due to software or hardware failure of the component.
5. *Component repair* to mitigate the effect of failure, either a repair of the component or the link connection is carried out.

It includes the recognition and diagnosis of the fault.

6. *Carrier aggregation* to support large bandwidth for capturing the high data rates, a technique called as Carrier Aggregation (CA) is used in LTE-A networks. CA is a specialized technology that enables UE and network to use more than one carrier frequencies, [21].

A UE in which CA configuration is formed connects to one primary serving (PS) eNBs and at most four secondary serving (SS) eNBs. The primary serving eNB is that eNB, which is configured in the first instance during connection establishment. Its main role is to provide security, NAS2 mobility information, S1 interface for configured eNBs, etc. A secondary serving eNB is that eNB, which may be configured after connection, establishment to give additional resources. It can be added or removed or reconfigured by RRC during the intra-LTE handover for aimed primary

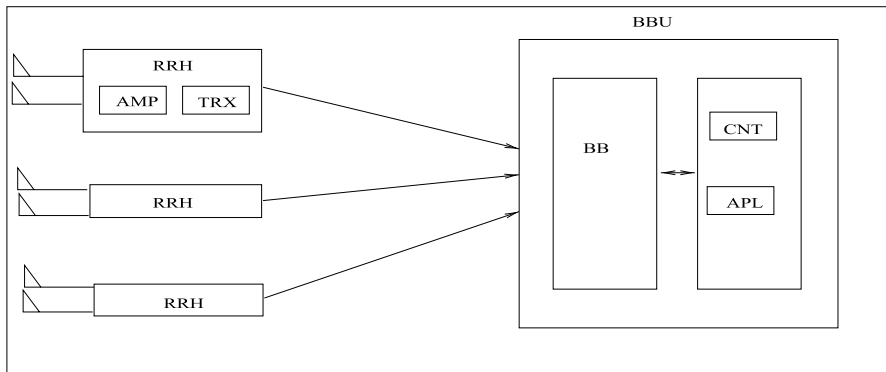


Fig. 2 Basic structure of an eNB

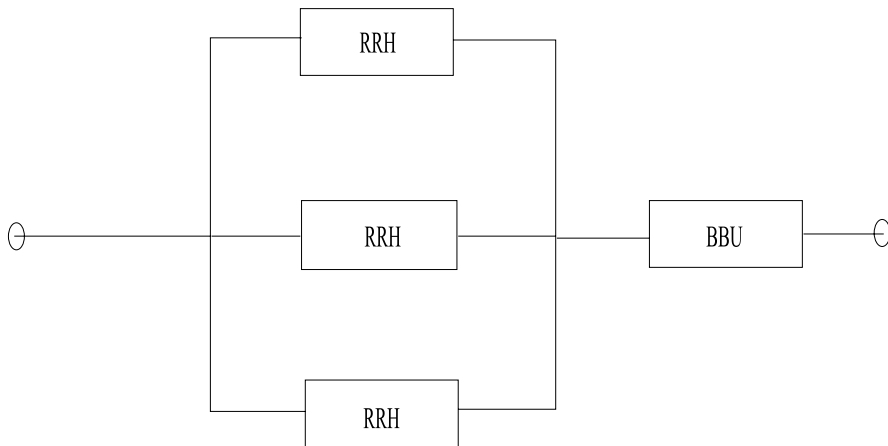


Fig. 3 RBD of an eNB

serving eNB. Also, the release of a secondary serving eNB configuration is network based and not regulated by the UE [27].

Now, before proceeding to the segments which discuss reliability and availability of an eNB, let us introduce the architecture of an eNB. As above mentioned, LTE-A network system is comprised of two major parts: E-UTRAN and EPC.

Consider the E-UTRAN part of the LTE-A networks. It consists only of eNB's on the network side, which are connected to each other via X2 interface.

Each eNB comprises of up to three Radio Heads (RRH) and one Baseband Unit (BBU), where an RRH is responsible for transmitting and receiving of wireless signals and a BBU is responsible for digital baseband signal processing termination of S1 and X2 line. To connect these two components an optical interface connection is established. The basic structure of an eNB is depicted in Fig. 2.

Next, we discuss the reliability and availability of an eNB.



Fig. 4 RBD for EPC

3.2 Reliability and availability at level 1: an eNB without repair

Let $R_{eNB}(t)$ be the reliability of i th eNB at time t in the network area. RBD for the same is shown in Fig. 3. Let reliability for the components, RRH and BBU at time t be denoted by $R_{RRH}(t)$ and $R_{BBU}(t)$, respectively. Also, let the time of failure of RRH and BBU be $Exp(\lambda_{RRH})$, $Exp(\lambda_{BBU})$, respectively. Then, we have

$$\begin{aligned} R_{eNB}(t) &= \left[1 - [1 - R_{RRH}(t)]^3 \right] \times R_{BBU}(t) \\ &= \left[1 - [1 - e^{(-\lambda_{RRH}t)}]^3 \right] \times e^{(-\lambda_{BBU}t)}. \end{aligned} \quad (1)$$

Further, let $A_{eNB}(t)$ denotes the instantaneous availability of i th eNB at time t . Let instantaneous availability for RRH and BBU at time t be denoted by $A_{RRH}(t)$ and $A_{BBU}(t)$, respectively. Further, on assuming the independent repair of all components, the expression for the instantaneous availability of eNB at time t can be written as follows:

$$A_{eNB}(t) = \left[1 - [1 - A_{RRH}(t)]^3 \right] \times A_{BBU}(t).$$

Next, we discuss the reliability and availability in the EPC part of the network.

3.3 Reliability and availability at level 2: in link connections

Evolved Packet Core (EPC) consists of MME, S-GW, and P-GW. In the hardware configuration, this may lie in various combinations [20]:

1. Combine MME, S-GW as one unit and P-GW as a separate unit. Also, this configuration is advantageous, if using a 3G network.
2. MME is one unit. S-GW and P-GW are combined as another unit. This arrangement is advantage from implication point.

Note that in above two combinations, control entity makes less delay due to less internode signaling but the complexity of a single node increases. Also, in the case of a node failure, more loss may occur. Therefore, in this work, all entities MME, S-GW and P-GW are treated as different units, which makes it the most flexible and least error-prone arrangement. RBD for EPC is depicted in Fig. 4. Let $R_{MME}(t)$, $R_{S-GW}(t)$ and $R_{P-GW}(t)$ be the reliabilities of MME, S-GW, and P-GW at time t , respectively.

Let $R_{EPC}(t)$ be the reliability of EPC at time t . Further, let time to failure of MME, S-GW and P-GW be $Exp(\lambda_{MME})$, $Exp(\lambda_{S-GW})$ and $Exp(\lambda_{P-GW})$, respectively. Then, we have

$$\begin{aligned} R_{EPC}(t) &= R_{MME}(t) \times R_{S-GW}(t) \times R_{P-GW}(t) \\ &= e^{(-\lambda_{MME}t)} \times e^{(-\lambda_{S-GW}t)} \times e^{(-\lambda_{P-GW}t)}. \end{aligned} \quad (2)$$

Further, let $A_{EPC}(t)$ be the instantaneous availability of EPC at time t . Let $A_{MME}(t)$, $A_{S-GW}(t)$ and $A_{P-GW}(t)$ be the instantaneous availabilities of MME, S-GW, and P-GW at time t , respectively. Also, assuming independent repair of all components, we can write an expression for the instantaneous availability of EPC at time t as follows:

$$A_{EPC}(t) = A_{MME}(t) \times A_{S-GW}(t) \times A_{P-GW}(t). \quad (3)$$

In the next subsection, we consider reliability and availability of the LTE-A networking system in the mesh topology. Mesh topology is a type of orientation which is considered among eNBs in LTE-A networks, [27].

3.4 Reliability and availability at level 3: mesh topology virtual network

Network reliability: It concerns with the probability that a network can support the desired network operation in an environment of random component failures. For network reliability, communication among eNBs is the primary concern.

Network availability: It is the percentage of the total network bandwidth available to route the traffic. When averaged over time, network availability effectively reflects the frequency and impact of failures in a given network.

Assume that K denotes the number of eNBs which are operational in the network area, initially. Out of these K number of eNBs, one will act as a PS eNB and others will act as SS eNBs [28, 29]. If there is a fault in PS eNB, then UE will again form an initial connection with one of SS eNB, and that eNB will start to work as PS eNB. In this article, it is assumed that all the eNBs are identical and their failures are independent of each other. Communication in LTE is primarily between the eNBs. Hence, in communication among eNBs, the reliability of the network is dependent upon the number of eNBs operational amongst the eNBs that can communicate within a transmission range. Therefore, a network is reliable if one or more eNB(s), amongst the group of eNBs, is(are) operational. A fixed transmission range is assumed for the eNBs. In our study, we assume that K eNBs communicate within a transmission range. Assuming that the eNBs are identical at time t , in eNB to eNB communication.

In case of the mesh topology, each of the K eNB's is connected to remaining $K - 1$ eNBs. Then, for these K communicating eNBs within a transmission range, there shall be $\binom{K}{2}$ number of possible distinct connections. Also, the reliability of a single connection is given by $(R_{eNB}(t))^2$, at time t .

Now, let $R_{network}(t)$ be the reliability of the network at time t , then it is given by the following expression

$$\begin{aligned}
 R_{network}(t) &= \left[1 - \left[1 - (R_{eNB}(t))^2 \right]^{\binom{K}{2}} \right], \\
 &= \left[1 - \left[1 - e^{(-2\lambda_{eNB}t)} \right]^{\binom{K}{2}} \right].
 \end{aligned} \tag{4}$$

MTTF: The expected failure time during which an eNB is expected to perform successfully, or the eNB's mean time to failure (MTTF).

Let $MTTF_{network}$ and $\lambda_{network}$ be the MTTF of network and rate of failure of the network, respectively. Therefore, $MTTF_{network}$ and $\lambda_{network}$ can be obtained as follows:

$$MTTF_{network} = \int_0^{\infty} R_{network}(t) dt, \tag{5}$$

$$\lambda_{network} = \frac{1}{MTTF_{network}}. \tag{6}$$

Let $A_{network}(t)$ be the instantaneous availability of the network at time t , then it is given by

$$A_{network}(t) = \left[1 - (1 - (A_{eNB}(t))^2)^{\binom{K}{2}} \right], \tag{7}$$

which can be further investigated using $\lambda_{network}$, obtained in Eq. (6).

Now, we move to survivability modeling which is discussed as the lower level CTMC models. This switching will help us in understanding and assessing the impact of failures and unavailabilities of components on overall LTE-A network system.

4 Survivability model

In this section, first, we discuss the importance of reliability and availability in LTE-A networks and their corresponding end to end CTMC models. Second, we construct a performance model which is further truncated appropriately to obtain the survivability model. In addition, without loss of generality, authors assume that link fault and power faults in an eNB are independent of each other. Then, we discuss the end to end reliability and availability model for LTE-A networks system considering a fixed number of eNB's in the beginning of the connection establishment.

The relative importance of availability and reliability depends on the application service. For example, services in which Mean Time To Repair (MTTR) is very small, availability is the primary concern. However, services related to multimedia

which are connection-oriented require a long MTTF, then reliability becomes the primary concern. In this work, LTE-A networks is considered, in which multimedia applications and real-time data transmission at the high rate, are the basic requirements.

Therefore, reliability is the primary concern and availability is the secondary concern in terms of hierarchical ethics.

For the purpose of mathematical modeling, consider LTE-A network area consisting of K number of eNB's.

Further, consider the following notations:

- K : Number of eNB's in the network area,
- $Y(t)$: Number of non failed eNB's at time t ,
- λ : The rate of failure of an eNB,
- μ : The rate of repair of an eNB,
- p_1 : Probability of a power fault at an eNB, $0 < p_1 < 1$,
- p_2 : Probability of a link fault at an eNB, $0 < p_2 < 1$,
- $\frac{1}{\delta_1}$: Average switching delay due to a power fault,
- $\frac{1}{\delta_2}$: Average switching delay due to a link fault,
- $p_{i,j}(t)$: Transient probability that CTMC is in state (i, j) at time t , where $(i, j) \in S_1$, and $S_1 = \{(i, j) : i = 0, 1, \dots, K, j = 0, 1, 2\}$,
- $p_{i,j}$: Steady-state probability that CTMC is in state (i, j) , where $(i, j) \in S_1$,

Define

$$Z(t) := \begin{cases} 0, & \text{if there is no fault in eNB at time } t, \\ 1, & \text{if there is a power fault in eNB at time } t, \\ 2, & \text{if there is a link fault in eNB at time } t. \end{cases}$$

Now, $\{(Y(t), Z(t)), t \geq 0\}$ is a two dimensional stochastic process with state space S_1 . With an assumption that failure, repair, link fault and power fault of an eNB follows the exponential distribution, and are independent of each other, the stochastic process $\{(Y(t), Z(t)), t \geq 0\}$ becomes a time homogeneous CTMC as depicted in Fig. 5.

4.1 End to end availability for LTE-A networks in case of faults and failure

Let $A_{end_to_end}$ be the steady-state probability that end to end network is available and is given by the expression

$$A_{end_to_end} = \sum_{i=1}^K p_{i,0}. \quad (8)$$

Under the constraint that network system is up as long as l number of eNBs are working well, then end to end steady-state availability is given by

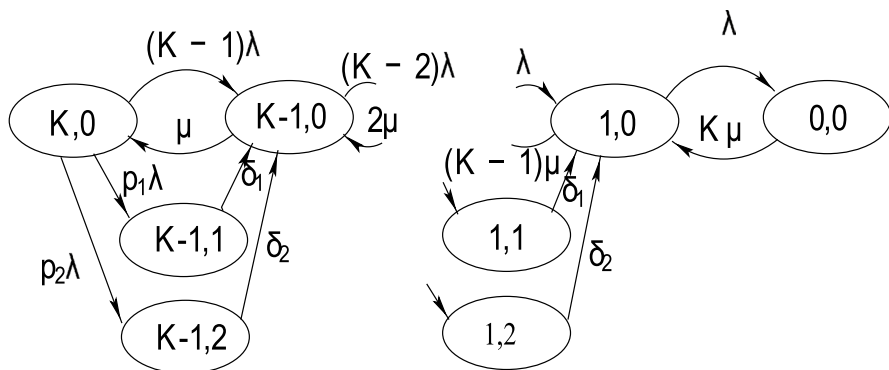


Fig. 5 End to end availability model for LTE-A networks

$$A_{end_to_end}(l) = \sum_{i=l}^K p_{i,0}.$$

Further, let transient end to end availability and expected interval availability be denoted by $A_{end_to_end}(l, t)$ and $E[A_{NB}(l, t)]$, respectively, and are given by

$$A_{end_to_end}(l, t) = \sum_{i=l}^K p_{i,0}(t), \quad (9)$$

$$E[A_{NB}(l, t)] = \frac{1}{t} \sum_{i=l}^K \int_0^t p_{i,0}(x) dx. \quad (10)$$

4.2 Reliability for LTE-A networks in case of faults and failure

During the process of transmission, an eNB may become faulty due to internal dysfunction and not to be able to transmit packets. Figure 6 depicts the CTMC model for the same.

Let $R_{end_to_end}(t)$ be the probability that end to end connection is reliable at time t , and is given by the expression

$$R_{end_to_end}(t) = 1 - p_{0,0}(t). \quad (11)$$

Hence, MTTF is given by

$$MTTF = \int_0^{\infty} R_{end_to_end}(t) dt. \quad (12)$$

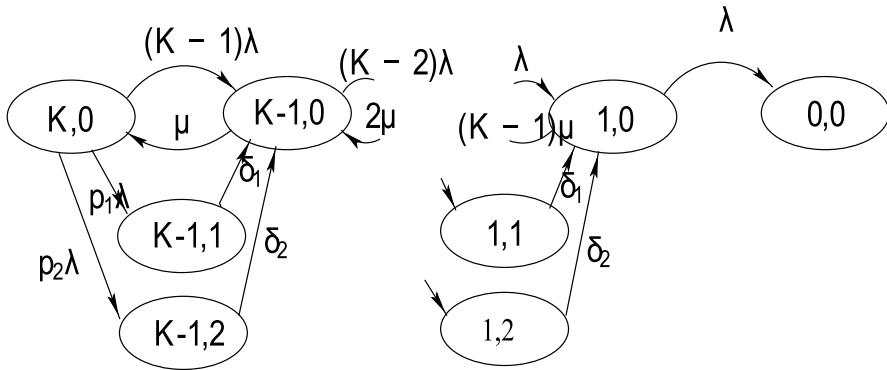


Fig. 6 Reliability model when an eNB fails

Furthermore, a composite model for performability⁶ and survivability is developed in the next subsection for analyzing the performance attributes.

4.3 The composite model for survivability and availability

In this subsection, system survivability and availability are obtained, using the probability of it being in a state. Network survivability is measured by system performance under the frequency of occurrence of failures, and its impact on the system performance. The combination of the availability measure and the transient measures together determine the overall system survivability [8]. Hence, a composite model is discussed which combines the availability and survivability. Also, a CTMC model for the same is depicted in Fig. 7.

Consider the following notations:

- $U(t)$: Number of weighted eNB's with load, say, L at time t ,
- $\frac{1}{\beta}$: Average time in which an eNB becomes weighted with load $\geq L$,
- $\frac{1}{\alpha_1}$: Average time in which an eNB gets free from weighted load $\leq L$,
- $\pi_{i,j,k}(t)$: Transient probability that CTMC is in state (i, j, k) at time t ,
where $(i, j, k) \in S_2$, and $S_2 = \{(i, j, k) : i, j = 0, 1, \dots, K, k = 0, 1, 2\}$,
- $\pi_{i,j,k}$: Steady-state probability that CTMC is and is in state (i, j, k) ,
where $(i, j, k) \in S_2$, and is given by

$$\pi_{i,j,k} := \lim_{t \rightarrow \infty} \Pr[(Y(t), U(t), Z(t)) = (i, j, k)].$$

Now, $\{(Y(t), U(t), Z(t)), t \geq 0\}$ becomes a three dimensional stochastic process with state space S_2 as shown in Fig. 7. With an assumption that β and α_1 follow the exponential distribution, the stochastic process $\{(Y(t), U(t), Z(t)), t \geq 0\}$ is a

⁶ Performability is a composite measure a system's performance and its dependability.

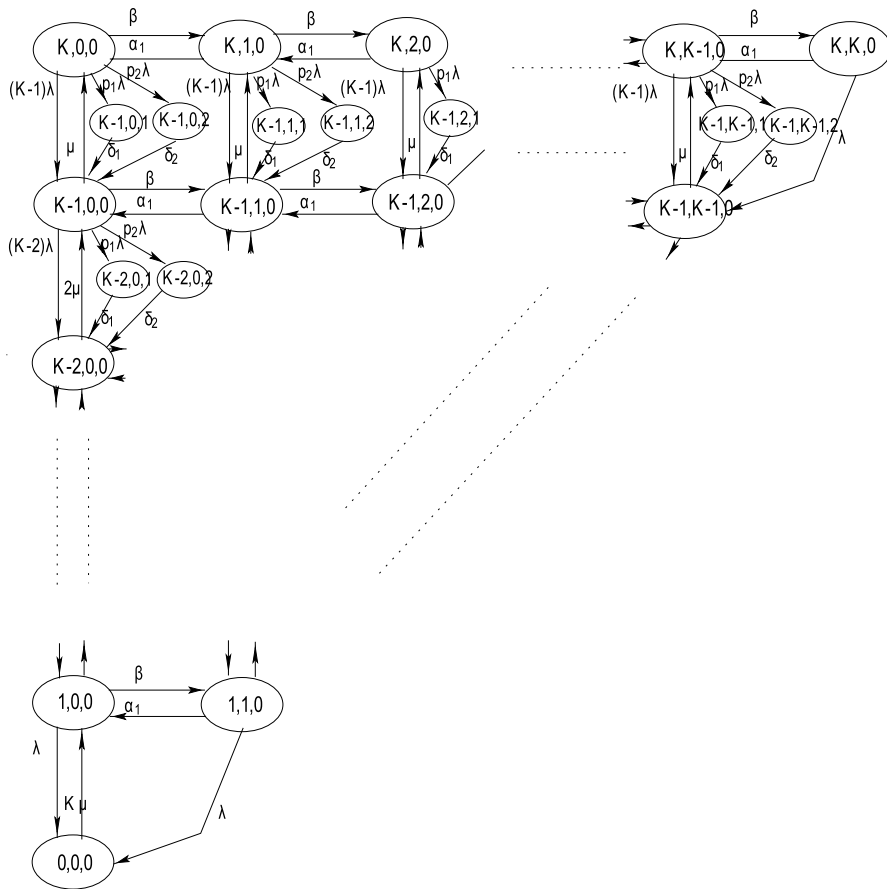


Fig. 7 The composite model for survivability and availability

time-homogeneous CTMC. Further, in the next subsection, a survivability analysis is performed for the aforementioned composite model.

4.4 Survivability analysis

Survivability it is the property of a system, subsystem, equipment, process, or procedure that provides a defined degree of assurance that the named entity will continue to function during and after a natural or man-made disturbance [7]. Examples of natural disasters are lightning strikes, mid-air collisions, crashes, earthquake, and tsunami, etc., whereas examples of man-made disturbances are software design errors, hardware degradation, human errors, corrupted data, etc., [30].

Define

T : Random variable denoting network system downtime,
 $F(t)$: Cumulative distribution function of T at time t .

Excess Delay due to failure (EDF) it measures the excess delay in accessing the network due to a hardware failure in the eNB. Further, let EDF_b and EDF_a be the expected excess delay due to failure before and after the natural disaster, respectively.

Also, since $T \sim \exp(\mu)$, then Expected Excess Delay (EED) is defined as

$$EED = \int_0^{\infty} t dF(t) = \int_0^{\infty} t \mu e^{-\mu t} dt.$$

Now, when a reward rate is assigned to each down state equals to EED, then EDF_b and EDF_b at time t , i.e., $EDF_b(t)$, as given in [31], are obtained by

$$\begin{aligned} EDF_b &= \sum_{i=1}^K \sum_{j=0}^i \lambda \cdot EED \cdot \pi_{i,j,0} \\ &= \sum_{i=1}^K \sum_{j=0}^i \frac{\lambda}{\mu} \cdot \pi_{i,j,0}, \end{aligned} \quad (13)$$

and

$$\begin{aligned} EDF_b(t) &= \sum_{i=1}^K \sum_{j=0}^i \lambda \cdot EED \cdot \pi_{i,j,0}(t) \\ &= \sum_{i=1}^K \sum_{j=0}^i \frac{\lambda}{\mu} \cdot \pi_{i,j,0}(t), \end{aligned} \quad (14)$$

where $\pi_{i,j,0}(t) = Pr[(Y(t), U(t), Z(t)) = (i, j, 0)]$.

Further, to understand the impact of unavailability of an eNB and its hardware failure, an analysis is performed in the next subsection.

4.5 Impact of an eNB's unavailability and its failure

An eNB can receive or transmit a packet if it is operational. Transmission of packets can be blocked due to various reasons such as an eNB failure, link failure, PS is already loaded with more than required messages, etc. In this subsection, a study is performed for their impact on the network system.

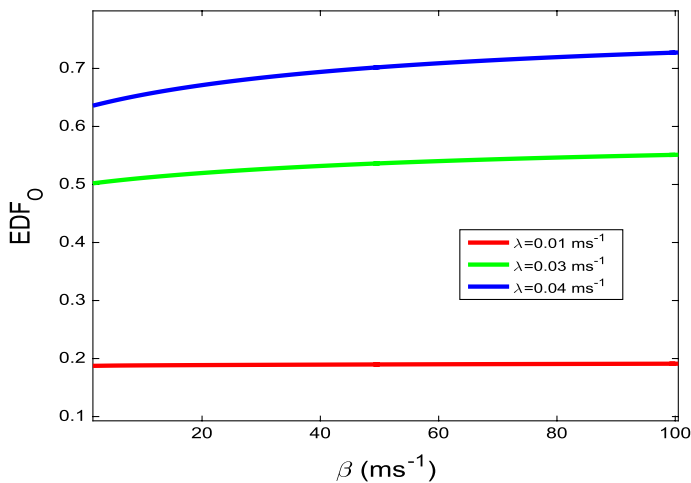
Let the transient blocking probability obtained from the composite model be $p_{eNB}^b(t)$ at time t , and is obtained by

$$p_{eNB}^b(t) = \sum_{i=0}^K \sum_{j=0}^2 \pi_{(i,j)}(t).$$

Let $B_{eNB}(t)$ be the total blocking probability of eNB due to hardware failure or overload at time t , and is given by

Table 1 List of various parameters and their respective rates

Parameter	Value	Parameter	Value
λ	0.01 ms^{-1}	μ	0.05 ms^{-1}
β	200 ms^{-1}	α_1	500 ms^{-1}
p_1	0.5	p_2	0.5
δ_1	1000 ms^{-1}	δ_2	100 ms^{-1}
λ_{RRH}	0.01 h^{-1}	λ_{BBU}	0.008 h^{-1}
λ_{MME}	0.1 h^{-1}	λ_{S-GW}	0.05 h^{-1}
λ_{P-GW}	0.02 h^{-1}		

**Fig. 8** EDF_b with respect to β

$$B_{eNB}(t) = (1 - R_{eNB}(t)) + R_{eNB}(t) \cdot p_{eNB}^b(t) \quad (15)$$

where $R_{eNB}(t)$ is given in Eq. (1).

5 Numerical analysis

In this section, numerical illustration is presented for the theoretical results discussed before in this article. Performance metrics, such as blocking probability, end to end availability, reliability, etc., are investigated, to assess the behavior of the system under various condition. Table 1 shows the value of parameters considered for the numerical analysis.

Using Eq. (13) tradeoff between EDF_b and β is illustrated in Fig. 8 for different values of packet arrival rate. It is observed that with an increase in λ , EDF_b increases. Also, with an increase in β , EDF_b increases slightly and becomes constant after a fixed point. It shows that excess delay due to failure before the disaster

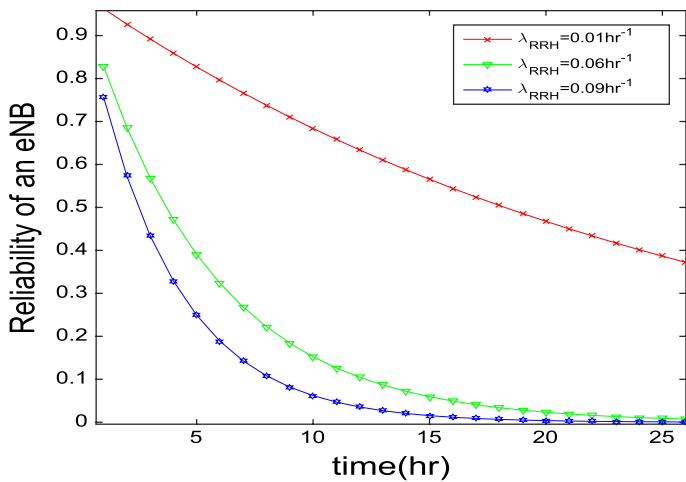


Fig. 9 Reliability of an eNB, when $\lambda_{BBU} = 0.008\text{ h}^{-1}$

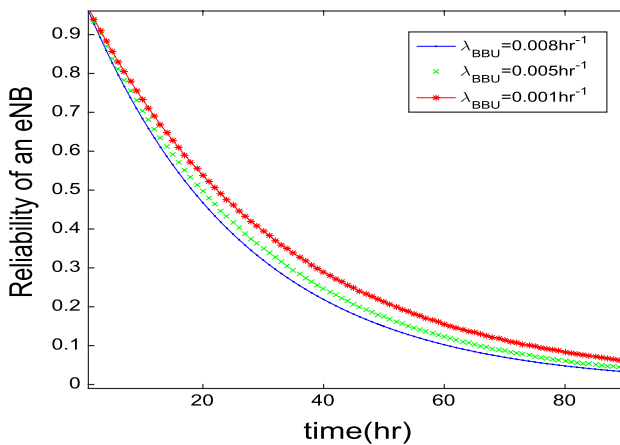


Fig. 10 Reliability of an eNB, when $\lambda_{RRH} = 0.01\text{ h}^{-1}$

increases, with an increase in packet arrival rate. Furthermore, it can be noted that, the rate of packet arrival affects the excess delay due to failure before the disaster (EDF_b), more in comparison to rate at which eNB becomes weighted.

5.1 Reliability

Reliability of an eNB and LTE-A network, are obtained from Eqs. (1) and (4), which are shown in Figs. 9 and 10, respectively. In Figs. 9 and 10, it is observed that, the reliability of eNB decreases with time as the λ_{RRH} or λ_{BBU} increases. Further, it is noted that the reliability decreases gradually with time. In Figs. 11 and 12 reliability of the LTE-A network is shown for mesh topology. We observe that the reliability

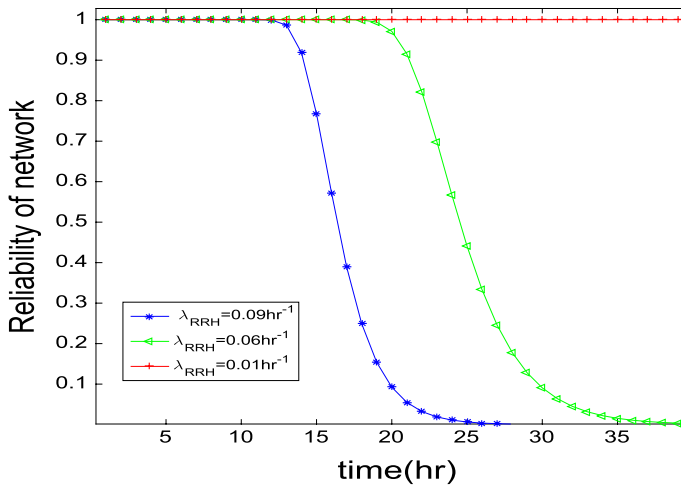


Fig. 11 Reliability of LTE-A network, when $\lambda_{BBU} = 0.008 \text{ h}^{-1}$

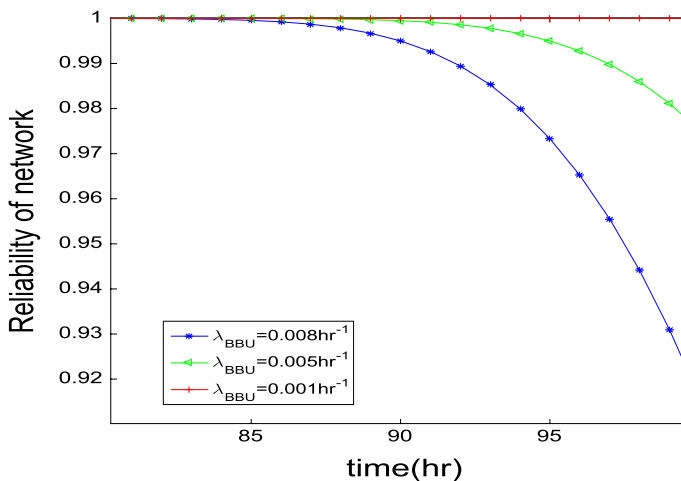


Fig. 12 Reliability of LTE-A network, when $\lambda_{RRH} = 0.01 \text{ h}^{-1}$

for network decreases with time as the λ_{RRH} or λ_{BBU} increases, respectively. Further, we inspected that with an increase in time, it decreases.

From Figs. 9 and 10, we detect that with the increase in failure rate of components, the reliability decreases which is an expected scenario.

However, in the case of the reliability LTE-A network, change in the failure rate of the component of eNB, make a significant amount of deviation in the reliability of the network, which is an unanticipated observation. The reason for this unanticipated observation could be, skipping any important modeling aspect or assumptions which we have taken for the sake of mathematical modeling convenience.

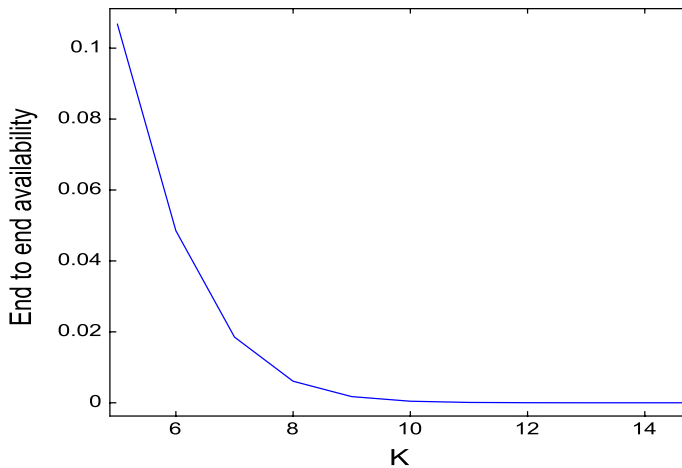


Fig. 13 End to end availability

5.2 End to end availability

Figure 13 shows the end to end availability ($A_{end_to_end}$) as obtained in Eq. (8) with respect to the number of eNBs. It is observed that as the number of eNB's increases, the availability decreases and becomes constant after a certain value of K . It concludes that with an increase in the number of eNBs in the network area, the end to end availability decreases.

We observed that it becomes difficult to make the connection from one end to the other end, when the number of eNBs increases in the network area, which is an unlikely observation. The reason for this unlike observation could be, skipping any important modeling aspect or assumptions which we have taken for the sake of mathematical convenience.

Now, using Eqs. (11) and (12), the reliability of LTE-A networks is computed in case of eNB failure. In Fig. 14, we observe that reliability of LTE-A networks decreases as the time increases.

5.3 Survivability

In this subsection, the steady-state probabilities of the composite model are used to quantify the survivability. The steady-state blocking probability for the composite model is denoted by $\pi_{(K,K,0)}$. After the first failure without repair, blocking probability becomes $\pi_{(K-1,K-1,0)}$ which quantifies the survivability of the network after the first failure and without repair in the system. The numerical result shows that $\pi_{(K-1,K-1,0)}$ increases with an increase in β as depicted in Fig. 15. Also, with an increase in λ , it decreases. It concludes that survivability decreases with an increase in packet arrival rate whereas it increases, with an increase in the rate at which an eNB becomes weighted with load L .

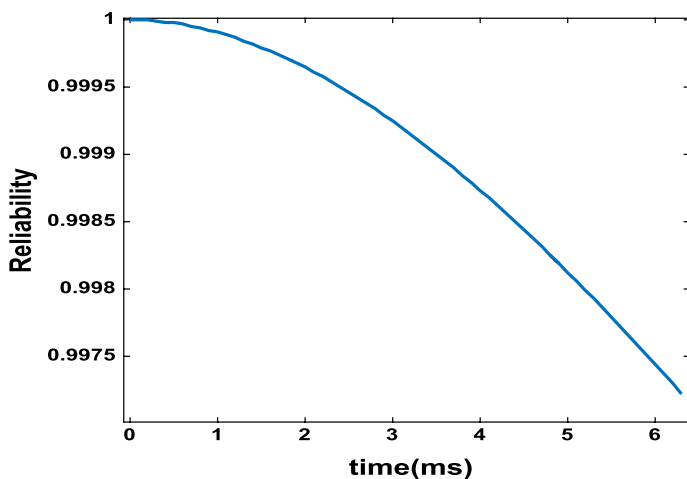


Fig. 14 Reliability of LTE-A networks in case of an eNB failure

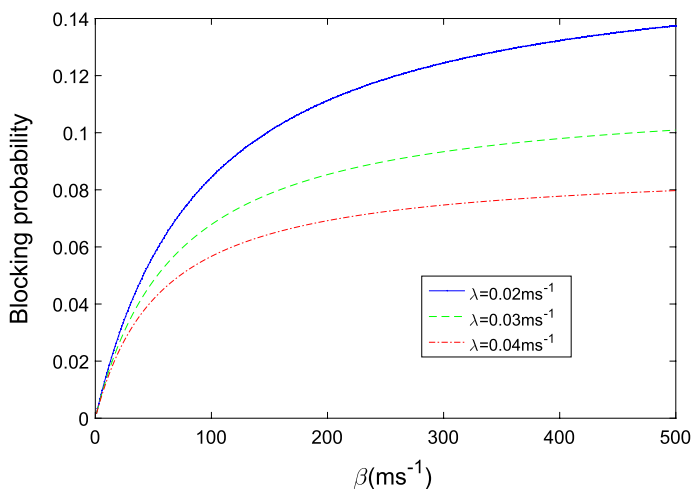


Fig. 15 Survivability after the first failure and without repair

6 Conclusion and future work

In this work, a novel hierarchical model is presented for the performance analysis of LTE-A networks, which is further classified into the upper level and lower level models. Upper level models are RBDs whereas lower level models are CTMCs. This classification is performed to capture a realistic approach towards modeling because dependent behavior and repair of failed components, etc., are not taken into account by an RBD model. Assuming exponential distribution for failure and repair of components, dependability measures are investigated. Further, these measures

such as reliability, availability, blocking probability, etc., can be used in providing essential guidelines for the improvement in network designing and QoS of the user. In our future research, we shall compare the existing analytical results, with results obtained from simulated scenario. Also, authors plan to use the semi-Markov approach to provide the realistic modeling.

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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