A Multirate Loss Model of Quasi-Random Input for the X2 Link of LTE Networks

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***Abstract*—In this paper, first we review a multirate loss model, whereby we can assess the call-level Quality of Service (QoS) of the Long Term Evolution (LTE) X2 link supporting calls of different service-classes with fixed bandwidth requirements. The X2 interface connects directly two neighboring evolved NodeBs and is mainly responsible for the transfer of user-plane and control-plane data during a handover. In the model, the X2 interface is modelled as a link of fixed capacity. Handover calls are accepted in the X2 link whenever available bandwidth exists. Secondly, we propose a multirate loss model where calls arrive in the X2 link according to a quasi-random process and compete for the available bandwidth under the Complete Sharing (CS) policy. The CS policy allows calls to enter the system when available bandwidth exists. We propose recursive formulas for the calculation of time and call congestion probabilities as well as link utilization for the CS policy.**

Keywords-LTE; X2; Quasi-random process; congestion; recursive formula.

I. INTRODUCTION

Long Term Evolution (LTE) networks provide increased throughputs via better spectrum exploitation and the use of multiple antennas, minimized latencies and a relatively simplified (the so-called "flat") architecture for the Evolved Universal Mobile Telecommunication System (UMTS) Terrestrial Radio Access Network (E-UTRAN) [1].

The main components of an LTE network are the Evolved Packet Core (EPC) and the E-UTRAN. The EPC is responsible for the management of the core network components and the communication with the external network. The E-UTRAN provides air interface, via evolved NodeBs (eNBs), to a User Equipment (UE) and acts as an intermediate node handling the radio communication between the UE and the EPC. Each eNB covers a specific cell and exchanges traffic with the core network through the S1 interface. An active UE is quite likely to cross the boundary of the source cell, causing a handover. A handover is the process of a seamless transition of the UE's radio link from the source eNB to one of its neighbors. During this transition, the direct logical interface (link) between two neighboring eNBs – the X2 link – is used, for the user data arriving to the source eNB via the S1 link, to be transferred to the target eNB (Figure 1).

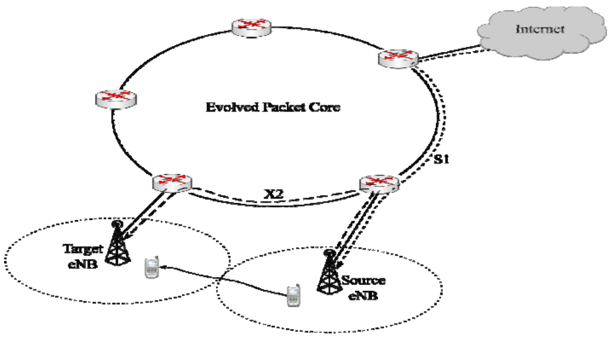

Figure 1. The S1 interface and the X2 interface between source and target eNBs.

The X2 interface is mainly used for the handover operation but it also supports load management and inter-cell interference coordination functions. However, considering that load management requires a constant but negligible bandwidth and assuming homogeneous LTE networks, in which interference coordination is not used [2] [3], we consider only the bandwidth required for the handover support. Based on the above, the X2 link carries both control and user plane traffic. However, according to [4][5], control plane traffic is negligible compared to user plane traffic. Therefore, we study herein user plane traffic only.

The determination of congestion probabilities in the X2 link can be based on multirate teletraffic loss models [2] [4][5]. In [2], a simple model is proposed by Blogowski, Klopfenstein and Renard (BKR model) that studies the impact of UE mobility in congestion probabilities. A circular source cell is considered, that accommodates a finite number of users, who generate quasi-random handover traffic [6] and have different bandwidth requirements. All UEs are considered having a constant velocity and moving in a straight line. The X2 link is modeled as a link of fixed capacity that accepts handover calls if their total bandwidth requirement is available upon their arrival. The calculation of congestion probabilities is based on analytical formulas that take into account UEs mobility, but can be complex in the case of large systems with large capacities and many service-classes. This is because enumeration and processing of the state space are required. In [4], a richer stochastic model is proposed by Widjaja and La Roche (WLR model), which is based on a

 ISBN: 978-1-61208-625-5

fluid mobility model [7][8] and the classical Erlang Multirate Loss Model (EMLM) [9][10]. Calls arrive in the X2 link according to a Poisson process, have fixed bandwidth requirements and compete for the available bandwidth under the Complete Sharing (CS policy). In the CS policy, a call is accepted in the system if its bandwidth requirement is available. Otherwise, the call is blocked and lost without further affecting the system. Although the BKR and WLR models provide similar congestion probability results, we adopt the WLR model since: a) basic performance measures including congestion probabilities, link utilization and average number of calls in the system can be recursively determined, without the need of state space processing (which is essential in [2]), b) various other bandwidth sharing policies (e.g., the bandwidth reservation policy, also known as guard channel policy, [11]-[16], the multiple fractional channel reservation policy [17]-[19] or the threshold policy [20]-[26]) can be applied in the X2 link, based on [4] and c) various handover arrival processes can be studied, e.g., the quasi-random arrival process, the batched Poisson process or an ON-OFF process [27]-[32]. Finally, in [5], a multirate loss model is proposed, based on the EMLM, assuming that traffic in the X2 link is elastic. Elastic traffic refers to calls whose allocated bandwidth is not fixed during their lifetime in the system. To model the bandwidth sharing policy in the case of elastic traffic the processor sharing discipline is considered [33]-[40].

In this paper, we study the X2 link at call-level and analyze it as a multirate loss system. To this end, we extend the WLR model to include the quasi-random arrival process (WLR-q model). In the quasi-random process, calls are generated by a finite number of users, a realistic assumption in the case of handover calls. Thus, the quasi-random process is smoother than the random (Poisson) process where calls are generated by an infinite number of users [12], [41]-[45].

This paper is organized as follows: In Section II, we review the WLR model of [4]. In Section III, we propose the WLR-q model. In Section IV, we present analytical TC probabilities results for the proposed model and the model of [4]. We conclude in Section V.

II. Review of The WLR Model

Consider a circular source cell of radius R, which accommodates Poisson arriving calls of K different service-classes. Calls of service-class k (k=1,…,K) follow a Poisson process with arrival rate λ_k and have a generally distributed service time, μ_k^{-1}. Contrary to the BKR model, in the WLR model a fluid mobility model is considered for the determination of the offered traffic-load in the X2 link.

The fluid mobility model of [4] considers traffic flow as the flow of a fluid. Such a model can be used to model the behavior of macroscopic movement (i.e., the movement of an individual UE is considered of little significance) [8]. This fluid mobility model formulates the amount of traffic flowing out of a circular region of a source cell to be proportional to the population density within that region, the average velocity, and the length of the region boundary. For a circular region with a population density of ρ_k (UEs of service-class k per km^2), an average velocity of v_k, and a diameter of L=2πR, the UE crossing rate per unit time, CR_k, from a source to any neighbor cell is:

$$CR_k = \rho_k v_k L/\pi = 2\rho_k v_k R \qquad (1)$$

Based on the above and assuming Poisson handover traffic, the offered traffic-load of service-class k calls, a_k, in the X2 link equals [4]:

$$a_k = p_A(k)\frac{\rho_k v_k L}{\pi}\delta = 2p_A(k)\rho_k v_k R\delta \qquad (2)$$

where: $p_A(k) = \lambda_k/(\lambda_k + \mu_k)$ is the probability that a service-class k UE is active (i.e., when there exists a Radio Resource Control (RRC) connection between a UE and eNB) and δ is the interruption time of the radio link between the source eNB and the UE.

Let b_k be the data rate of an active service-class k UE and n_k be the in-service service-class k UEs in the X2 link. By defining the corresponding vectors $\boldsymbol{n} = (n_1,...,n_k,...,n_K)$ and $\boldsymbol{b} = (b_1,...,b_k,...,b_K)$ then the occupied bandwidth j in the X2 link can be expressed as:

$$j = \boldsymbol{nb} = \sum_{k=1}^{K} n_k b_k,\ \ j = 0,1,...,C_{X2} \qquad (3)$$

To determine the X2 link occupancy distribution, $q(j)$, it is assumed that UEs compete for the available bandwidth under the CS policy. Following the analysis of the EMLM, the un-normalized values of $q(j)$'s can be determined by the classical Kaufman-Roberts recursive formula [9][10]:

$$q(j) = \left\langle \begin{array}{c} 1\ for\ j=0 \\ \frac{1}{j}\sum_{k=1}^{K} a_k b_k q(j-b_k)\ for\ j=1,...,C_{X2} \\ 0\ otherwise \end{array} \right\rangle \qquad (4)$$

Based on $q(j)$'s we calculate the Time Congestion (TC) probabilities of service-class k, B_k, by the formula [4]:

$$B_k = \sum_{j=C_{X2}-b_k+1}^{C_{X2}} G^{-1} q(j) \qquad (5)$$

where: $G = \sum_{j=0}^{C_{X2}} q(j)$ is the normalization constant.

TC probabilities are determined by the proportion of time the system is congested and measured by an outside observer. Call Congestion (CC) probabilities refer to the probability that a UE is blocked and lost. Due to the assumption of Poisson arrivals, TC and CC probabilities coincide (PASTA property, [6]).

III. THE PROPOSED WLR-q MODEL

In the WLR model, calls compete for the available bandwidth of the X2 link under the CS policy. In this section, we extend the WLR model by considering the case of quasi-random traffic.

Consider the X2 link of fixed capacity C_{X2} that accommodates K different service-classes. Calls of service class k (k =1,…,K) require b_k channels and come from a finite source population N_k while the mean arrival rate of service-class k idle sources is $\lambda_{k,fin} = (N_k - n_k)s_k$ where n_k is the number of in-service calls and s_k is the arrival rate per idle source. Assuming a population density of $\rho_k = N_k / \pi R^2$ for a circular region and that the UEs are always active, then the total offered traffic load of service-class k is $2\frac{N_k v_k \delta}{\pi R}$ while the offered traffic-load per idle source of service-class k is given by $a_{k,fin} = 2v_k\delta / \pi R$ (in erl). This arrival process is known as a quasi-random process [6]. If $N_k \to \infty$ for k = 1,…,K, and the total offered traffic-load remains constant, then the arrival process becomes Poisson.

The global balance equation for state $\boldsymbol{n}=(n_1,\ldots,n_k,\ldots,n_K)$, expressed as *rate into state* $\boldsymbol{n}$ *= rate out of state* $\boldsymbol{n}$, is given by:

$$\begin{aligned}&\sum_{k=1}^{K}(N_k - n_k + 1)s_k P(\boldsymbol{n}_k^-) + \sum_{k=1}^{K}(n_k+1)\delta^{-1}P(\boldsymbol{n}_k^+)\\ &= \sum_{k=1}^{K}(N_k - n_k)s_k P(\boldsymbol{n}) + \sum_{k=1}^{K} n_k \delta^{-1} P(\boldsymbol{n})\end{aligned} \quad (6)$$

where:
$\boldsymbol{n}_k^+ = (n_1,\ldots,n_{k-1},n_k+1,n_{k+1},\ldots,n_K)$ $\boldsymbol{n}_k^- = (n_1,\ldots,n_{k-1},n_k-1,n_{k+1},\ldots,n_K)$ and $P(\boldsymbol{n}), P(\boldsymbol{n}_k^-), P(\boldsymbol{n}_k^+)$ are the probability distributions of the corresponding states $\boldsymbol{n}, \boldsymbol{n}_k^-, \boldsymbol{n}_k^+$, respectively.

The proposed model has a Product Form Solution (PFS) for the determination of the steady state probabilities $P(\boldsymbol{n})$ due to the fact that local balance exists between adjacent states $\boldsymbol{n}_k^-, \boldsymbol{n}$ or $\boldsymbol{n}, \boldsymbol{n}_k^+$. The local balance equations, for k=1,…,K, are of the form:

$$(N_k - n_k + 1)a_{k,fin}P(\boldsymbol{n}_k^-) = n_k P(\boldsymbol{n}) \quad (7)$$

where: $a_{k,fin} = s_k \delta$.

The PFS that satisfies both (6) and (7) is the following:

$$P(\boldsymbol{n}) = G^{-1}\left(\prod_{k=1}^{K}\binom{N_k}{n_k}a_{k,fin}^{n_k}\right) \quad (8)$$

where $G \equiv G(\boldsymbol{\Omega}) = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}}\left(\prod_{k=1}^{K}\binom{N_k}{n_k}a_{k,fin}^{n_k}\right)$.

To avoid the complex calculations based on the PFS, we prove a recursive formula for the calculation of the X2 link occupancy distribution, $q_{fin}(j)$, of the proposed WLR-q model. By definition:

$$q_{fin}(j) = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} P(\boldsymbol{n}) \quad (9)$$

where $\boldsymbol{\Omega}_j$ is the set of states whereby the occupied bandwidth is exactly j, i.e. $\boldsymbol{\Omega}_j = \{\boldsymbol{n}\in\boldsymbol{\Omega} : \boldsymbol{nb} = j\}$ and $\boldsymbol{\Omega}$ is the system's state space, $\boldsymbol{\Omega} = \{\boldsymbol{n} : 0 \le \boldsymbol{nb} \le C_{X2},\ k = 1,\ldots,K\}$.

Since $j=\boldsymbol{nb} = \sum_{k=1}^{K} n_k b_k$ we write (9) as follows:

$$jq_{fin}(j) = \sum_{k=1}^{K} b_k \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} n_k P(\boldsymbol{n}) \quad (10)$$

To determine the $\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} n_k P(\boldsymbol{n})$ in (10), we sum both sides of (7) over $\boldsymbol{\Omega}_j$:

$$\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j}(N_k - n_k + 1)a_{k,fin}P(\boldsymbol{n}_k^-) = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} n_k P(\boldsymbol{n}) \quad (11)$$

The left hand side of (11) can be written as:

$$\begin{aligned}&\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j}(N_k - n_k + 1)a_{k,fin}P(\boldsymbol{n}_k^-) =\\ &N_k \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} a_{k,fin}P(\boldsymbol{n}_k^-) - \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j}(n_k - 1)a_{k,fin}P(\boldsymbol{n}_k^-)\end{aligned} \quad (12)$$

Since $\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} a_{k,fin}P(\boldsymbol{n}_k^-) = a_{k,fin}q_{fin}(j-b_k)$ the first term of the right hand side of (12) becomes:

$$N_k \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} a_{k,fin}P(\boldsymbol{n}_k^-) = N_k a_{k,fin} q_{fin}(j-b_k) \quad (13)$$

The second term of the right hand side of (12) is written as:

$$\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j}(n_k - 1)a_{k,fin}P(\boldsymbol{n}_k^-) = a_{k,fin}y_{k,fin}(j-b_k)q_{fin}(j-b_k) \quad (14)$$

where $y_{k,fin}(j-b_k)$ is the average number of service-class k calls in state $j-b_k$.

Based on (13) and (14), (12) becomes:

$$\begin{aligned}&\sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j}(N_k - n_k + 1)a_{k,fin}P(\boldsymbol{n}_k^-)\\ &= a_{k,fin}\left(N_k - y_{k,fin}(j-b_k)\right)q_{fin}(j-b_k)\end{aligned} \quad (15)$$

Equation (11) due to (15) takes the form:

$$\left(N_k - y_{k,fin}(j-b_k)\right)a_{k,fin}q_{fin}(j-b_k) = \sum_{\boldsymbol{n}\in\boldsymbol{\Omega}_j} n_k P(\boldsymbol{n}) \quad (16)$$

Equation (10) due to (16) is written as:

$$jq_{fin}(j) = \sum_{k=1}^{K} \left(N_k - y_{k,fin}(j - b_k) \right) a_{k,fin} b_k q_{fin}(j - b_k) \quad (17)$$

In the recursive formula of (17), the values of $y_{k,fin}(j - b_k)$ are not known. To determine them, we use a lemma of [46]. According to that lemma, two stochastic systems are equivalent and result in the same congestion probabilities, if they have: a) the same traffic description parameters $(K, N_k, a_{k,fin})$ where k=1,…,K and b) exactly the same set of states.

Our purpose is, therefore, to find a new stochastic system, whereby we can determine $y_{k,fin}(j - b_k)$. The bandwidth (channel) requirements of calls and the capacity in the new stochastic system are chosen according to the following two criteria: 1) conditions (a) and (b) are valid and 2) each state has a unique occupancy j.

Based on the above, state j is reached via the previous state $j - b_k$. Thus, $y_{k,fin}(j - b_k) = n_k - 1$ and (17) is given by:

$$q_{fin}(j) = \begin{cases} 1, & for\ j = 0 \\ \frac{1}{j}\sum_{k=1}^{K}(N_k - n_k + 1)a_{k,fin} b_k q_{fin}(j - b_k), & for\ j = 1,...,C_{X2} \\ 0, & otherwise \end{cases} \quad (18)$$

In (18), the values of n_k are unknown. The determination of n_k's requires the state space determination of the equivalent system, a complex procedure especially for large capacity systems that accommodate many service-classes. Because of this we approximate n_k in state j, $n_k(j)$, as $y_k(j)$, when Poisson arrivals are considered, i.e., $n_k(j) \approx y_k(j)$. Thus, we determine $q_{fin}(j)$'s via the formula:

$$q_{fin}(j) = \begin{cases} 1, & for\ j = 0 \\ \frac{1}{j}\sum_{k=1}^{K}(N_k - y_k(j - b_k))a_{k,fin} b_k q_{fin}(j - b_k), & for\ j = 1,...,C_{X2} \\ 0, & otherwise \end{cases} \quad (19)$$

where the values of $y_k(j)$'s are given by:

$$y_k(j) = \begin{cases} \frac{a_k q(j - b_k)}{q(j)} & for\ \ j \geq b_k \\ 0 & otherwise \end{cases} \quad (20)$$

As far as the values of $q(j)$'s in (20) are concerned, they can be determined by (4).

Having determined $q_{fin}(j)$'s we calculate the TC probabilities of service-class k calls, B_k, as follows:

$$B_k = \sum_{j=C_{X2}-b_k+1}^{C_{X2}} G^{-1} q_{fin}(j) \quad (21)$$

where: $G = \sum_{j=0}^{C_{X2}} q_{fin}(j)$ is the normalization constant.

CC probabilities of service-class k, $B_{CC,k}$, can be determined via (21) where $q_{fin}(j)$'s are calculated (via (19)) for a system with N_k - 1 traffic sources. As far as the X2 link utilization, U_{X2}, is concerned, it is given by:

$$U_{X2} = \sum_{j=1}^{C_{X2}} jG^{-1} q_{fin}(j) \quad (22)$$

The following algorithm summarizes the order of TC probability and X2 link utilization calculations in the proposed WLR-q model:

1) Determine $q(j)$'s via (4).
2) Determine $y_k(j)$'s via (20).
3) Determine $q_{fin}(j)$'s via (19).
4) Determine B_k's via (21) and U_{X2} via (22).

IV. NUMERICAL RESULTS

In this section, we compare the analytical results of TC probabilities, obtained by the proposed WLR-q model for various values of velocity and cell radius. For comparison, we also present the corresponding analytical results obtained in the case of the WLR model.

Consider an X2 link of capacity C_{X2} = 50 channels that accommodates calls (handovers in progress) of K=3 service-classes with channel requirements: b_1 = 1, b_2 = 5 and b_3 = 12, respectively. Calls of each service-class arrive in the link according to a quasi-random process and are generated by a finite number of sources, N_k = 50, for k=1, 2, 3 (it is supposed that, at any moment, the total number of active users inside a cell -who are candidate to perform a handover- along with those performing a handover, is constant). Furthermore, let δ = 0.05 sec, and velocities v_1 = v_2 = v_3 = 30 km/h. In the x-axis of Figures 2-4, the velocity of all users increases in steps of 2 km/h. So, point 1 refers to: (v_1, v_2, v_3) = (30, 30, 30) while point 11 to: (v_1, v_2, v_3) = (50, 50, 50).

Figures 2-4 present the analytical TC probabilities of each service-class for three different values of the cell radius R = 150, 200 and 250 m. Based on these results, we conclude that: 1) TC probabilities are lower in the case of quasi-random traffic (WLR-q model) compared to the corresponding TC probabilities obtained in the case of the Poisson process (WLR model). 2) The increase of velocity increases TC probabilities, since it is more probable for a call to make a handover. 3) The increase of R reduces TC probabilities since it becomes less likely that a call will make a handover.

V. CONCLUSION

We review a multirate loss model for the call-level analysis of the X2 link in LTE networks. The X2 link is modelled as a multirate loss system that accommodates handover calls from different service-classes with fixed bandwidth requirements. Handover calls are accepted in the X2 link whenever available bandwidth exists. Otherwise, call blocking occurs. Furthermore, we propose a multirate loss model for the call-level analysis of the X2 link when the arrival process becomes quasi-random. We provide recursive formulas for the calculation of various performance measures including TC and CC probabilities. As a future work, we intend to study the applicability of the bandwidth reservation and the multiple fractional channel reservation policies in the proposed model.

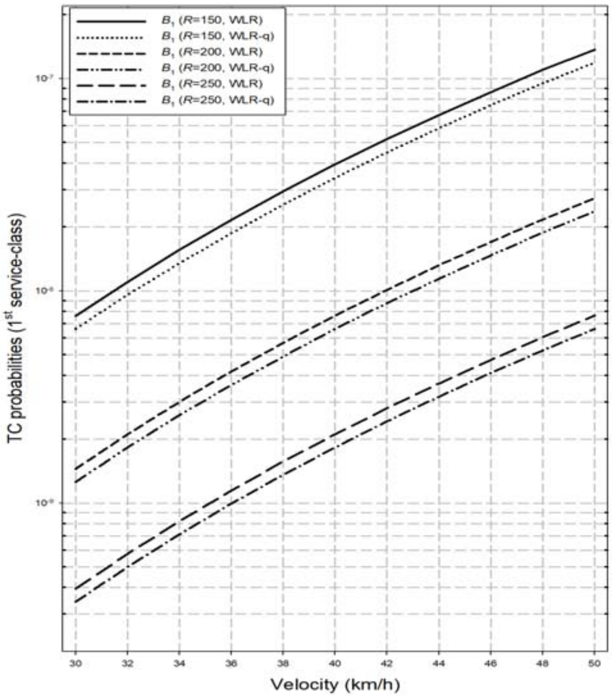

Figure 2. TC probabilities of the 1st service-class.

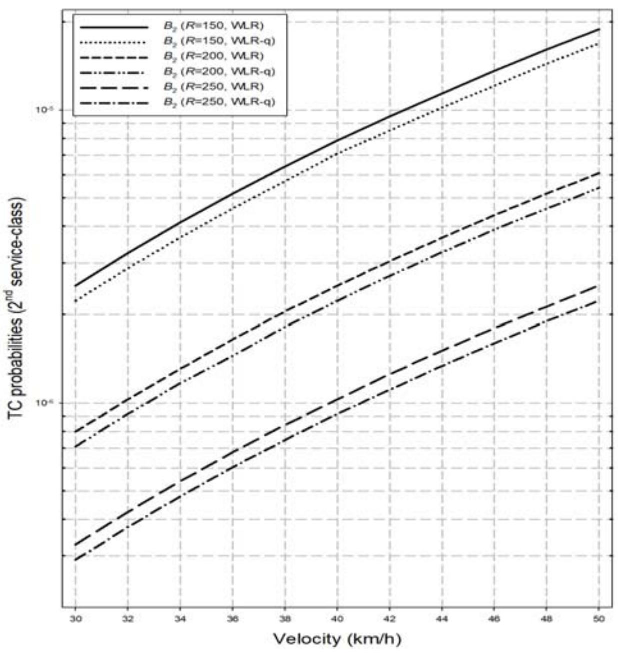

Figure 3. TC probabilities of the 2nd service-class.

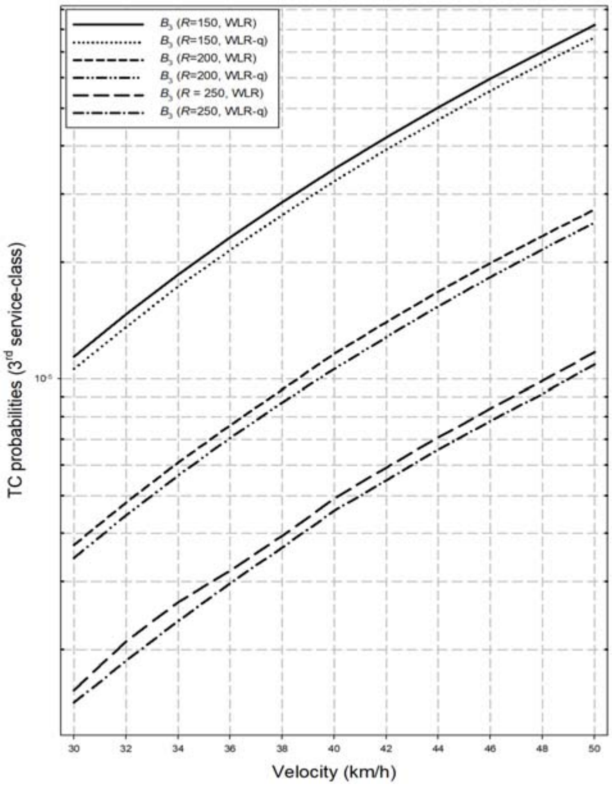

Figure 4. TC probabilities of the 3rd service-class.

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