Ruin Theory Based Modeling of Fair Spectrum Management in LTE-U

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Abstract—Long Term Evolution-Unlicensed (LTE-U) is a 5G enabling technology in which both LTE and Wi-Fi systems operate together using the same frequency spectrum. LTE can co-exist with Wi-Fi in both 2.5GHz and 5GHz bands for fully utilizing the spectrum. Aggregating these two technologies while implementing a fair allocation of resources among them is a challenge. Moreover, the LTE technology provides better spectral efficiency and is more bandwidth hungry, thus, it can consume more spectrum which is unfair for Wi-Fi systems. Therefore, appropriate spectrum management scheme is needed to be developed that can maintain the fairness among the two coexisting technologies. This paper proposes a ruin theory based redundant spectrum allocation to LTE-U users while providing sufficient fairness to Wi-Fi systems.

Index Terms—LTE-U, Ruin Theory, Surplus Process

I. INTRODUCTION

Spectrum scarcity is a big issue of 5G mobile networks where higher data rate demands have been increased from past few years. In order to meet these demands, new spectrum resources are being discovered as well as efforts are made to improve the available spectrum utilization in a better way. One of the possible options to meet the spectral needs of bandwidth hungry LTE cellular networks is to utilize unlicensed spectrum [1]. Utilization of unlicensed Wireless LAN (WLAN) or Wi-Fi spectrum in cellular networks along with licensed 5G spectrum is a good solution to spectrum scarcity if Wi-Fi systems are not suppressed significantly.

Unlicensed spectrum utilization in cellular networks has been proposed in different forms including LTE-U, Licensed Assisted Access (LAA) and MuLTEfire [2]. In LAA, unlicensed spectrum is only used for enhancing downlink data rate services in cellular systems. Other control information and uplink communication is operated on licensed spectrum. In MuLTEfire, cellular systems solely operate on unlicensed band.

Although both LTE and Wi-Fi systems can operate on same spectrum frequency band, the spectrum access schemes of both systems are quite different. LTE uses dynamic spectrum access allocated in TDD fashion, while Wi-Fi is working on contention based spectrum access where multiple stations compete to access the channel [3]. LTE works in a centralized way while Wi-Fi is operated in distributed manner.

Due to these dissimilarities, LTE can suppress Wi-Fi spectrum if traditional ways of maximizing the shared spectrum efficiency are applied in both infrastructures. To mitigate the differences in channel access and to merge the two systems for accessing the unlicensed spectrum such that the Wi-Fi system cannot suffer, a fair spectrum sharing technique is required [4]. Fairness to Wi-Fi systems can be provided by applying Listen Before Talk (LBT) protocol in cellular system which is similar to carrier sensing in Distributed Coordination Function (DCF) mode of Wi-Fi systems.

To decrease the differences in both access technologies and to reduce the interference offered by cellular systems to Wi-Fi, small cells base stations (SBSs) are best option for implementing LTE-U. Power of SBSs is kept comparable to Wi-Fi Access Points (APs) to reduce interference. SBSs are useful in deploying high density HetNets [5]. A significant work has been done in HetNets for high spectrum efficiency and resource allocation [6], [7].

Fully utilizing the spectrum resources for LTE cellular networks while satisfying sufficient Wi-Fi throughput is a challenge in LTE-U. This paper proposes a ruin theory based model to minimize the interference offered by LTE systems to Wi-Fi systems while maximizing the spectral performance of LTE.

Ruin or risk theoretic modeling can be mapped to LTE-U system due to similarities among insurance/customer and LTE/Wi-Fi systems work-flows. In ruin theory, insurance company takes premiums from customers and fulfill their random claims on demand [8]. When we apply the ruin theory in LTE-U, we can model the unlicensed spectrum resources as surplus process where random claims from Wi-Fi collisions can be handled using ruin theory.

Probability of ruin is used as a measure to allocate unlicensed channels to cellular users. If probability of ruin is high, it is unfair to allocate channels to cellular systems therefore a corresponding fraction of unlicensed channels are allocated. Optimization problem is formulated to choose the fraction of resources according to the probability of ruin obtained from surplus process modeled for Wi-Fi systems.

This paper proposes ruin theory based modeling to formulate the surplus process for unlicensed spectrum. Based on the probability of ruin, the resources to LTE systems are allocated while providing fairness to Wi-Fi systems. This fairness is provided by limiting the cellular systems from ruining the resources of Wi-Fi systems.
Rest of the paper is organized in the following way. Section II gives brief literature review of LTE-U. System model is presented in Section III followed by Problem Formulation and Optimization Model in Section IV and Section V. Section VI gives simulation results and Section VII concludes the paper.

II. RELATED WORK

LTE-U is a hot topic in 5G dense Heterogeneous Networks today and a lot of work is being done in this research area. [9] proposes a Dynamic Channel Selection, Carrier Aggregation and Fraction Spectrum Access while providing fairness for Wi-Fi users. Almost Blank Subframe (ABSF) can be utilized to provide fairness for Wi-Fi users. A fairness criteria for LTE-U can be defined where Spectrum Sharing is considered fair if LTE small cell interference is same as other Wi-Fi APs.

The work in [10] propose to share the redundant resources with other operators by introducing an encouragement mechanism. Authors have tried to introduce fairness by blanking some subframes for Wi-Fi. The authors have assumed two controllers for Wi-Fi and LTE and these controllers are managed by same operator. Joint use of licensed and unlicensed spectrum for LTE is proposed in [11]. Users which are closer to the base station can be allocated unlicensed channels with low power so that Wi-Fi users are not affected by high power transmission. The authors proposed to use unlicensed spectrum only when licensed spectrum is fully utilized already.

In [12], the authors utilized decoupling in uplink and downlink cellular systems in LTE-U. Echo state networks are used in order to solve the optimization problem. A listen before talk based adaptive channel access of unlicensed spectrum for LTE-U is proposed in [13]. Collision probability for Wi-Fi users is maintained by adjusting backoff window for channel access. The paper in [14] proposes a Nash bargaining game to maximize the sum rate of cellular users by expanding the licensed spectrum with augmented unlicensed band.

Centralized user association and spectrum allocation to HetNets users is proposed in [15] where multiple radio access technologies (RATs) are utilized for spectrum allocation. Joint association and allocation problem is formulated and converted to convex problem. The paper [16] proposes offloading of cellular users on Wi-Fi networks. Multi objective problem is formulated for maximizing per user LTE throughput and minimum Wi-Fi throughput.

Traffic offloading from macro base station to small cell base stations (SBSs) has been proposed in HetNets but the spectrum scarcity is the bottleneck for such offloading [17], [18]. Another approach [19], [20] is to offload traffic from macro cell to device to device networks (D2D) but it has limitations in terms of distance between transmitter and receivers, i.e., close vicinity. LTE-U provides the solution to these problems by offloading traffic from licensed spectrum to unlicensed spectrum.

Ruin theory based fairness is a novel technique to apply in LTE-U and none of the aforementioned works has proposed this technique for providing fairness among cellular and Wi-Fi systems. Most of the literature focuses on maximizing the spectrum efficiency by allocating more channels to highly efficient LTE networks which can suppress the Wi-Fi networks significantly. Major contribution of this paper is to use ruin theory for fair spectrum offloading from licensed spectrum to unlicensed spectrum.

III. SYSTEM MODEL

Our system model consists of a single LTE small cell base station coexisting with W Wi-Fi access points represented by set \( \{1, 2, \ldots, W\} \). User Equipments (UEs) served by the small cell base station are represented by \( u \in UEs \) and mobile stations served by Wi-Fi access point \( w \in W \) are represented by wireless stations \( WSTs \).

![Fig. 1. System Model of LTE-U single small cell coexisting with multiple Wi-Fi APs](image)

Basic purpose of LTE-U is to meet the high data rate requirements of cellular users. Therefore, LTE-U is applied in downlink where unlicensed spectrum from Wi-Fi systems is used. Uplink communication in cellular network and control channels are operated on regular licensed band of LTE.

As shown in Fig. 1, all Wi-Fi Access Points (APs) and LTE small cell base station are sharing the same unlicensed spectrum. Therefore, orthogonal channels can be used by these APs and SBS because SBS can cause interference to all APs operating in the neighboring area. APs are operating on traditional DCF protocol of IEEE 802.11 wireless LAN. SBS is using Listen Before Talk to find out if the channel is free or occupied.
Throughput of Wi-Fi users can be obtained using the following relation [3]:

\[ r_w = \frac{P_{tr} P_s E[P]}{(1 - P_{tr}) T_s + P_{tr} P_s T_s + P_{tr} (1 - P_s) T_c} \]  \hspace{1cm} (1)

Where \( P_{tr} \) is the probability of at least one transmission, \( P_s \) is the probability of successful transmission, \( E[P] \) is expected packet length and \( T_s, T_c \) are duration of empty slot, successful transmission and collision respectively.

As there is only one SBS operating in our system model, there will be no interference from other cellular systems. This assumption is realistic even if we consider multiple cellular systems operating in the neighboring environment. Because each SBS is operating on unlicensed spectrum, it will be orthogonal to neighboring SBSs therefore it will get no interference from neighbours. However, a negligible interference will be offered by other APs while trying to access the channel. This interference is negligible because in DCF protocol, no communication is allowed while a transmission is in progress. Therefore, cellular SBS users will get the following SINR:

\[ r_i = 1 + \frac{p_i g_i}{\sigma^2} \]  \hspace{1cm} (2)

Where, \( p_i \) is the transmission power , \( g_i \) is the gain of UE \( i \) and \( \sigma \) is noise level. There is only single SBS in our system model; therefore, no interference offered from other surrounding base stations on unlicensed band.

IV. PROBLEM FORMULATION

In this section we formulate the problem.

A. Problem Statement:

Main goal of this paper is to maximize the rate for cellular networks while providing fairness to Wi-Fi networks. In order to provide fairness, certain constraints must be applied to limit the resources captured by the cellular SBS.

- Channels can only be allocated to UEs when no other transmission is in progress. This channel availability is determined using Listen Before Talk (LBT).
- In order to provide fairness to Wi-Fi users, a threshold throughput of Wi-Fi users is maintained. This threshold throughput is modeled with Ruin theory. The probability of ruin for Wi-Fi system is determined and spectrum is allocated to UEs based on this probability.

B. Surplus Process for Wi-Fi Throughput:

Wi-Fi throughput is improved in each transmission slot based on the number of channels available for Wi-Fi. In our system model, a fixed number of channels can be used orthogonally by Wi-Fi system without providing interference to the neighboring APs transmission.

On the other hand, Wi-Fi throughput is reduced by random number of collisions occurred. Each collision will reduce the overall throughput of Wi-Fi systems by fraction represented as \( r_w \). This throughput reduction also depends upon the size of colliding packet.

Based on throughput increase, using the available number of channels and throughput reduction as a result of random collisions, surplus Process can be modeled as:

\[ U(t) = \gamma + (ct) r_w - r'_w \sum_{t=1}^{N_t} X_t \]  \hspace{1cm} (3)

Where \( U(t) \) is the Wi-Fi throughput surplus, \( \gamma \) is the initial throughput, which is also the throughput threshold needs to be maintained for fairness to Wi-Fi. \( c \) is the the premium rate of surplus process which is the fixed number of channels used by Wi-Fi systems. \( \sum_{t=1}^{N_t} X_t \) is a compound process which is combination of two random variables \( N_t \) and \( X_t \). Here, \( N_t \) is the number of collisions till time \( t \) and \( X_t \) is the size of each colliding packet.

Probability of ruin is defined as the probability of getting the surplus less than 0. Ruin theoretic modeling is used to find this probability of ruin. Probability of Ruin \( \Psi(u) \) is defined as

\[ \Psi(u) = P[U(t) < 0] \]  \hspace{1cm} (4)

Ruin probability can be determined as

\[ \Psi(x) = \frac{\lambda \mu}{c} \exp \left( \frac{1}{\mu} - \frac{\lambda}{c} x \right) \]  \hspace{1cm} (5)

Where, \( \lambda \) is the arrival rate of collisions \( \mu \) is mean the packet size of colliding packet, \( c \) is the the premium rate which is the number of channels used by Wi-Fi system. \( x \) is considered to be the Surplus as given in Eq. 10.

This ruin probability is used to provide fairness to Wi-Fi systems. If probability of ruin is high, less resources will be allocated to cellular users to reduce interference for Wi-Fi systems.

V. OPTIMIZATION MODEL

This section will formulate the optimization problem for resource allocation to LTE system.

The decision variable of our problem is \( \alpha_k \in \{0, 1\} \) where, \( k \in \{0, 1, \ldots, c_u\} \); \( \alpha_k \) is the variable which indicates the proportion of the channel \( k \) to be allocated to LTE.

Our optimization model will take the ruin probability as a parameter from Wi-Fi system. This probability is used to limit the cellular system from swallowing unfair resources.

Channel availability is also assumed to be known by using Listen Before Talk algorithm on LTE SBS. \( \beta_k \in [0, 1] \) takes binary value for channel availability and this parameter is known before optimization problem is solved.
A. Optimization Problem:

Objective of the optimization problem is to maximize the rate of cellular users while satisfying the fairness and interference criteria.

\[
\text{Max} \sum_{k \in C_u} \sum_{i \in u} \alpha_k \beta_k \log(r_i)
\]

subject to

\[
\sum_{k \in C_u} \alpha_k \beta_k \leq c_u, \quad (6)
\]

\[
\sum_{k \in C_u} \alpha_k \beta_k \leq (1 - \Psi(u)) \sum_{k \in C_u} \beta_k, \quad (7)
\]

\[
0 \leq \alpha_k \leq 1 \quad (8)
\]

Eq. (6) limits the rate of cellular users by allowing channel allocation only when channel is idle. Idle state of channel is determined using the parameter \(\beta\). Eq. (7) gives the fairness constraint. Resources to be allocated to cellular users is limited by the fraction \((1 - \Psi(u))\) which indicates the fraction of unlicensed band available to cellular system not imposing significant degradation in Wi-Fi system.

Based on the information regarding the channel availability \(\beta\) and the probability of ruin \(\Psi(u)\), the problem can be solved at SBS. We solved this problem by using convex solver Jumpt in Julia programming language.

The probability of ruin \(\Psi(u)\) provides fairness to Wi-Fi systems. If \(\Psi(u)\) is higher then it is unfair to allocate the resources to LTE and vice versa. The proportion \(1 - \Psi(u)\) defines the fair proportion of channels which can be allocated to the LTE systems.

Outcome of the optimization problem is \(\alpha_k\) which is the proportion of each channel to be allocated to LTE users. Here

Algorithm 1 Fair Channel Allocation Algorithm

1: **Input**: \(\beta_u\), \(\Psi(u)\).
2: **initialize**: \(T_C = 0, T_s = 0, T_i = 0\).
3: for UEs do
4: **Run Optimization to compute** \(\alpha_k\); 
5: for ST's = \(\alpha_k + UEs + WSTs\) do 
6: Select Back-off for WSTs; 
7: if Transmission Successful then
8: **Update Throughput**; 
9: \(T_s + \); 
10: Select new Back-off; 
11: else Collision 
12: **Double b_{wind} size**; 
13: \(T_C + \); 
14: end if 
15: end for 
16: \(T \leftarrow T_C + T_s + T_i\), 
17: **Compute Throughput**; 
18: **Update** \(\Psi(u)\) 
19: end for 

\[B\] represents the total unlicensed bandwidth. The resource blocks allocated to each user can be found as.

\[r_b = B \sum_{k} \frac{\alpha_k}{u} \quad (9)\]

Where \(u\) is the total number of cellular users in the SBS. As a result, LTE rate can be found as

\[R_{LTE} = r_b \sum_{i \in UEs} \log_2(1 + \frac{P_i G_i}{\sigma^2}) \quad (10)\]

VI. SIMULATION RESULTS

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SYSTEM PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Values</td>
</tr>
<tr>
<td>(b_{wind_{min}})</td>
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</tr>
<tr>
<td>SIFS</td>
<td>16 (\mu s)</td>
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<tr>
<td>Ack Size</td>
<td>14 Byte</td>
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<tr>
<td>(Peak Bit Rate)</td>
<td>3000</td>
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<tr>
<td>(p_i)</td>
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</table>

This section presents the evaluation of our proposed solution for LTE-U using experimental results. One SBS of radius 200m is coexisting with uniformly distributed 3 Wi-Fi APs each with coverage area of 100m. As in LTE-U, SBS can coexist with Wi-Fi APs, the number of cellular users
in our system model are up to 10 UEs in each SBS. Fig. 2 shows the network topology consisting of SBS and coexisting APs. SBSs can use the redundant unlicensed band from each AP. Wi-Fi network setup is based on IEEE 802.11 basic DCF mode (without RTS/CTS). Other system parameters are listed in the Table I.

Results are taken against the increasing number of LTE users (UEs) for pure Wi-Fi without any effect of LTE interference, Wi-Fi coexisting with LTE without applying the proposed scheme, and finally, Wi-Fi coexisting with LTE while providing fairness using the proposed solution. Both Wi-Fi and LTE rate variations can be analyzed from the results Fig. 3 shows the throughput of Wi-Fi system vs the increasing number of LTE users. It can be seen that without any LTE stations, Wi-Fi throughput is maximum while it decreases significantly when LTE users are involved without providing any fairness. The proposed scheme (LTE-U) shows better results by providing fairness to Wi-Fi systems. Fairness is implied by using the probability of ruin while giving channel access to LTE users. It can be seen from the results that the proposed scheme prevents the LTE users to consume significant resources of Wi-Fi systems and therefore it provides fairness.

![Graph showing Wi-Fi Throughput vs Number of LTE Users](image)

Fig. 3. Throughput of Wi-Fi System vs the number of LTE Users

Fig. 4 shows the rate of LTE system vs the probability of ruin. It can be seen here that LTE has significantly higher rate when the probability of ruin is less and it reduces with the increase in ruin probability, because less resources are allowed to be allocated to LTE users with the increase in the probability of ruin. Also, it can be seen that LTE rate is reduced when there are more number of Wi-Fi stations (WSTs). It is because more WSTs may cause more collisions which may increase the probability of ruin.

![Graph showing LTE Rate vs Probability of Ruin](image)

**Fig. 4. Throughput of LTE Network vs the number of LTE Users**

**VII. CONCLUSION**

LTE-U is a promising solution of spectrum scarcity where redundant channels from Wi-Fi systems are allocated to cellular users while providing fairness to Wi-Fi and enhancing the cellular users data rate. This paper proposed a ruin theoretic based modeling of LTE-U for fair resource allocation. Surplus process is used for modeling the throughput of Wi-Fi system and probability of ruin is used in optimization model to allocate fair channel allocation. Simulation results reveal that fairness to Wi-Fi system is provided while improving the data rates for LTE.

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