A Hopfield Neural Networks Based Mechanism for Coexistence of LTE-U and WiFi Networks in Unlicensed Spectrum

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***Abstract*—Long-Term Evolution in the unlicensed spectrum (LTE-U) is considered as an indispensable technique to mitigate the spectrum scarcity in wireless networks. Typical LTE transmissions are contention-free and centrally controlled by the base station (BS); however, the wireless networks that work in unlicensed bands use contention-based protocols for channel access, which raises the need to derive an efficient and fair coexistence mechanism among different radio access networks. In this work, we propose a novel neural networks (NNs) based mechanism for the coexistence of an LTE-U base station (BS) in the unlicensed spectrum alongside with a WiFi access point (WAP). Specifically, we model the coexistence problem as a Hopfield Neural Network (HNN) based optimization problem that aims a fair coexistence considering both the LTE-U data rate and the QoS requirements of the WiFi network. Using the energy function of HNN, precise investigation of its minimization property can directly provide the solution of the optimization problem. Numerical results show that the proposed mechanism allows the LTE-U BS to work efficiently in the unlicensed spectrum while protecting the WiFi network.**

***Index Terms*—LTE-U, hopfield neural networks (HNNs), coexistence, resource allocation.**

I. Introduction

Mobile wireless traffic is continuously increasing, where mobile video traffic is the dominant part. Therefore, Cellular Network Operators (CNOs) must redesign their networks to meet the increasing data traffic and satisfy the required QoS of their users. In particular, CNOs aim to increase their network capacity which requires more spectrum bands. However, the licensed spectrum is scare and expensive. Recently, a lot of advances and improvements have been proposed for cellular networks to enhance its efficiency (i.e, MIMO, D2D, Cooperative Communication, etc.). However, the licensed spectrum scarcity remains the key bottleneck for mobile cellular networks. Therefore, extending cellular networks to the unlicensed spectrum is an effective approach to handle the spectrum scarcity challenge. Industry standardization organizations have developed a number of standards for LTE in the unlicensed spectrum such as LTE-U and Licensed-Assisted Access (LAA). LTE-U is standardized by LTE-U Forum and developed to work with 3GPP releases 11, 12, and 13. LAA, standardized in 3GPP release 13, is based on the Listen Before Talk (LBT) protocol [2], [3].

LTE-U transmissions are centrally controlled by the Base Station (BS). However, WiFi networks are based on a contention-based technique for channel access. Therefore, LTE-U may potentially degrade the performance of WiFi networks if not properly managed. Hence, this work introduces a harmonious coexistence mechanism for an LTE-U BS and a WiFi Access Point (WAP) in the unlicensed spectrum based on Neural Networks (NNs) technology.

A. Literature Review and Contributions

Different mechanisms to support the coexistence of cellular networks in the unlicensed bands have been introduced in literature [4]. Authors [5] propose an algorithm based on the LBT technique that allows an LTE BS to share the unlicensed bands with WAPs. The algorithm aims to optimize the network energy considering both the bandwidth and power allocation. Authors in [6] study the joint spectrum sharing and power control problem for vehicle-to-everything networks based on LTE-U technology. They divide time domain into two periods referred as *Content Free Period (CFP)* and *content period (CP)*. They also classified the vehicle user into safe and non-safe users based on their access categories. The non-safe vehicle user is allowed to content for unlicensed bands in CP. Authors in [7] consider a coexistence algorithm to allow multiple cellular network operators to work in unlicensed bands alongside with WiFi networks. They formulate a mathematical optimization problem that gives a trade-off between the data rate of LTE users and QoS satisfactions of WiFi users. Furthermore, the optimization problem is decomposed into two problems referred as resource allocation and time sharing problems. The one-sided matching game and the cooperative Nash bargaining game are leveraged to solve the resource allocation problem and the time sharing problem respectively. The work in [8] proposes an algorithm based on ON/OFF duty cycle mechanism. In this mechanism, LTE network transmits at the ON periods and stops its transmission during the OFF periods. The work in [9] proposes a cooperative Nash bargaining game based coexistence algorithm. Authors found optimal sharing time considering inter-operators interference. They leverage a heuristic algorithm to allocate resources to

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users. Authors in [10] formulate the problem of LTE-U/WiFi resource allocation as a non-cooperative game. They propose a machine learning based framework to solve the resource allocation problem. Hence, LTE BS can select their resources based on the network's states. Authors in [11] address the coexistence problem of LTE and WiFi networks using time-domain virtualization. They assume that there is a hypervisor in the LTE BS that can coordinate between LTE and WiFi transmissions. This paper introduces a coexistence algorithm based on the Hopfield Neural Networks (HNNs), i.e. HNNs belong to the Recurrent Neural Networks (RNNs). The proposed coexistence mechanism aims to maximize the LTE-U data rate[1] while protecting the WiFi network. We divide the time domain into equal duration time intervals referred as time windows and each window is composed of time slots. The proposed HNNs based algorithm classifies the time slots of each time window into *ON slots* and *OFF slots*, i.e. LTE-U BS works during the *ON slots* only and this allows the WiFi network to work during the *OFF slots*, aiming a fair coexistence. The main motivation to use HNNs is that it can give an on-line solution due to its ability to process in parallel and thus it can save the computation time. In summary, our contributions are:

- We model the coexistence problem as a HNN, where each time slot is represented as a neuron in HNN. Here, firing neurons, i.e. neurons with state 1, correspond to *ON slots* of which LTE-U BS can transmit over it while neurons with state 0 correspond to *OFF slots* of which LTE-U BS stops its transmission over it and this allows the WiFi network to transmit.
- We formulate an optimization problem with a binary variable that indicates whether a time slot is *ON slot* or OFF slot. The objective is to maximize the LTE-U network data rate while satisfying the QoS of the WiFi network. Furthermore, We modify the optimization problem and rewrite it in the HNN's energy function form. Therefore, the energy function's decreasing property is leveraged to solve the optimization problem.
- Numerical results demonstrate that the proposed mechanism allows both LTE-U and the WiFi networks to work harmoniously and efficiently.

The rest parts are as follows: section II gives a brief overview on NNs and HNNs. The system model is described in section III. Section IV introduces the proposed HNN based coexistence mechanism. Section V presents numeral results and discussion. Finally, the conclusion is presented in section VI.

II. An Overview on Hopfield Neural Networks

Recently, Artificial Neural Networks (ANNs) have become an effective method to solve the complicated optimization problems efficiently and give an online solution due to its parallel processing capability. ANNs composed of processing

[1]In this paper, the LTE-U data rate refers to data rate of LTE users that comes from unlicensed resources only

Fig. 1: Energy Function of HNNs

elements, i.e. neurons, that work together to solve a giving problem. Generally, ANNs are divided into two types according to its structure, *Feed-forward Networks* and *Feedback Networks or Recurrent Neural Networks (RNN)*. There are two ways to configure the ANNs:

1) *Training Model:* connection weights update its values based on a learning rule.
2) *Non-Training Model:* connection weights are set explicitly based on a prior knowledge.

HNNs are a non-training RNNs and the output of each neurons can be either '1' or '0' based on the neurons' input. Let w_{ij} be the connection weight between neurons i and j. In HNNs, the weight matrix has the following properties:

- *Symmetry:* the connection weights of all neurons are symmetric, i.e. for any two neurons i and j, $w_{ij} = w_{ji}$.
- *Zero-Diagonal:* the diagonal elements of the weight matrix are zero, i.e, for a neuron i, $w_{ii} = 0$.

The neurons in HNNs update its value according to

$$y_i(t+1) = \begin{cases} 1, & \text{if } \sum_j w_{ij} y_j(t) \geq \theta_i \\ 0, & \text{Otherwise,} \end{cases} \tag{1}$$

where $y_j(t)$ is the j^{th} neuron's state, and θ_i is the i^{th} neuron's threshold. In HNNs, there is a value related to each network state named as the energy of the network $E(y)$. The value of $E(y)$ either decreases or stays the same upon network neurons being updated. The energy function is defined as:

$$E(y) = \frac{-1}{2} \sum_i \sum_j w_{ij} y_i y_j + \sum_i \theta_i y_i. \tag{2}$$

The value of $E(y)$ decreases and converges to a stable state when updating neurons randomly [12], [13]. Fig. 1 shows the convergence of $E(y)$ when updating a neuron randomly in each iteration. As shown in Fig. 1, the value of $E(y)$ decreases in each iteration until convergence, i.e. reach a local minimum. We leverage this minimization property in this work

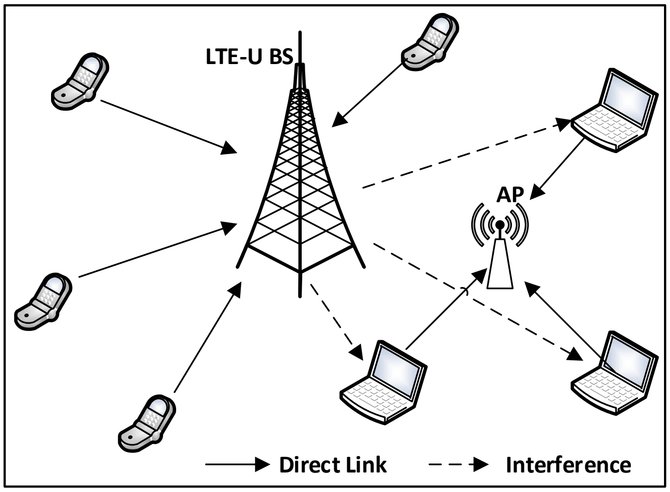

Fig. 2: System Model

by modeling and expressing the coexistence problem in terms of neuron states y_i. Therefore, we can calculate the weight matrix and thresholds by matching $E(y)$ and the formulated objective function.

III. System Model

We consider a wireless network consisted of an LTE-U BS and a WAP sharing the same unlicensed band as shown in Fig. 2. Let $\mathcal{U} = \{1, 2, ..., U\}$ be the set LTE-U users. The time domain is modeled as equal duration time windows with width of t_w. Each window is divided into equal duration slots t_s. The time slots (t_s), in each window, are assigned either to LTE-U BS or WiFi networks such that a harmonize coexistence is achieved. Let $\mathcal{S} = \{1, 2, ..., S\}$ denote the set of all slots in a window and let z_s be an indicator variable, where $z_s = 1$ means that LTE-U BS can transmits over the unlicensed band at time slot $s \in \mathcal{S}$ and at $z_s = 0$ the LTE-U stops its transmission in the unlicensed band and gives the opportunity to WiFi network to transmit. The major mathematical symbols used in this paper are presented in Table I.

LTE-U users share the bandwidth in terms of Resource Blocks (RBs). Thus, the data rate of a user u is calculated according to the Shannon formula as [14]

$$r_u^l(t) = \sum_{b \in \mathcal{B}} v_{u,b} f_b \log_2(1 + \beta \frac{p_u h_u(t)}{N_0 F}), \tag{3}$$

where $\mathcal{B} = \{1, 2, ..., B\}$ is the set of RBs and $v_{u,b}$ is the RB allocation result defined as

$$v_{ub} = \begin{cases} 1, & \text{if RB } b \text{ is allocated to user } u \\ 0, & \text{otherwise,} \end{cases} \tag{4}$$

f_b is the b^{th} RB bandwidth, F is the total available bandwidth, p_u is the transmission power of the user u, h_u is the user u channel gain, and β is defined as

$$\beta = 1.5/(-\ln(5BER)), \tag{5}$$

TABLE I: Summary of Notations

Symbol	Meaning
y_i	State of neuron i of HNN
w_{ij}	The connection weight between neurons in HNN
θ_i	Threshold of neuron i of HNN
$E(y)$	Energy function of HNN
$\mathcal{B}$	Set of all RBs
B	Number of RBs
$\mathcal{U}$	Set of all LTE-U users
U	Number of LTE-U users
$\mathcal{N}$	Set of all WiFi users
N	Number of WiFi users
$\mathcal{S}$	Set of all time slots in one time window
z_s	Indicator variable denotes if the time slot s is allocated whether to LTE-U BS or WAP
r_u^l	Instantaneous data rate of LTE-U user u
v_{ub}	RBs allocation indicator
f_b	Bandwidth of RB b
F	The total bandwidth
p_u	Transmission power
h_u	Channel gain of LTE-U uers u
N_0	Noise power
β	Constant related to BER, $\beta = 1.5/(-\ln 5BER)$
r_n^w	Saturation throughput of a WiFi user n
P_{tx}	Transmission probability in each time slot
P_{suc}	Probability of successful transmission
T_{SUC}	Time of which channel is busy because of a successful transmission
T_{col}	Time of which the channel is busy because of collisions
T_σ	Duration of empty slot
P_n	Transmission probability of each WiFi user
t_w	Window time width
δ	Propagation delay
C_{bit}	Channel bit rate
ACK	Acknowledgment time
$DIFS$	Distributed inter-frame space
ρ	Weight controls the preference of WiFi data rate

where BER represents the bit error rate. The data rate of a user u during a time window (t_w) can be calculated as

$$r_u^l(t_w) = \sum_{s=1}^{S} r_u^l(t_s) z_s, \tag{6}$$

where $r_u^l(t_s)$ is the data rate of the user u over the unlicensed band at time slot t_s and can be calculated based on the equation (3).

The data rate of a WiFi user n is defined as follows [15]

$$r_n^w = \frac{P_{tx} P_{suc} E[PacketSize]}{(1 - P_{tx})T_\sigma + P_{tx} P_{suc} T_{suc} + P_{tx}(1 - P_{suc})T_{col}}, \tag{7}$$

where P_{tx} is the transmission probability at a time slot and defined as $P_{tx} = 1 - (1 - P_n)^N$, where P_n is the user transmission probability. P_{suc} is the successful transmission probability and defined as $P_{suc} = NP_n(1 - P_n)^{(N-1)}$. The probability of all users are in back-off stage or detection stage (i.e., no user use channel) is defined as $(1 - P_n)^N$. T_{suc} is the busy channel time during a successful transmission, T_{col} is the busy channel time due to collisions, T_σ is the empty slot time duration, and finally $E[PacketSize]$ is the average packet size.

We consider that the WiFi networks access use the distributed coordination function algorithm with RTS/CTS access

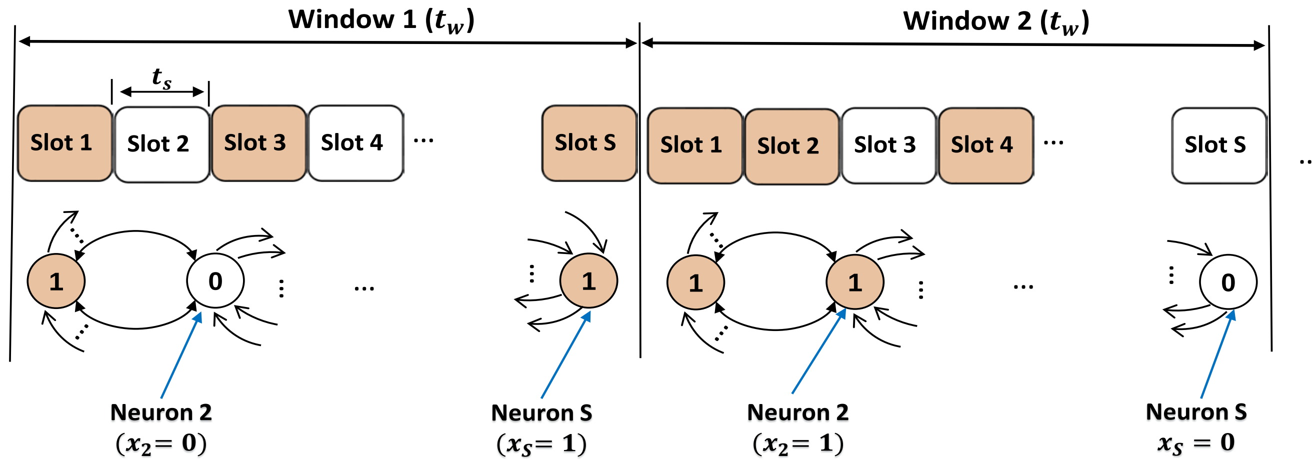

Fig. 3: The proposed HNN based model for the coexistence of LTE-U/WiFi

algorithm for channel access. Hence, we can calculate T_{col} and T_{suc} as follows [15]

$$\begin{aligned} T_{suc} =& RTS/C_{bit} + CTS/C_{bit} + (PacketHeader \\ &+ E[PacketSize])/C_{bit} + ACK/C_{bit} \\ &+ 3 * SIFS + DIFS + 4 * \zeta, \end{aligned} \tag{8}$$

$$T_{col} = RTS/C_{bit} + DIFS + \zeta, \tag{9}$$

where ζ is the propagation delay, C_{bit} is the channel bit rate, $DIFS$ is an abbreviation of the distributed inter-frame space, ACK is the acknowledgment time, RTS is the request to send, and finally CTS is the clear to send.

Let $n \in \mathcal{N}$ be a WiFi user connected to the WAP, its data rate during a t_w is given by

$$r_n^w(t_w) = \sum_{s=1}^{S} r_n^w\,(1 - z_s), \tag{10}$$

where r_n^w is defined in equation (7).

The objective is first to classify time slots into *ON/OFF slots* such that the data rate of the LTE-U network is maximized while protecting WiFi users and keeping their data rate at accepted level.

A. Problem Formulation

The proposed coexistence algorithm of LTE-U BS/WAP allows the BS to transmit in the unlicensed band during the *ON slots* and keeps it silent during the *OFF slots* to protect the WiFi transmissions and then achieve a fair coexistence. We formulate a problem that maximizes the data rate of LTE-U network in unlicensed band while protecting the WiFi transmissions and ensuring its QoS. Therefore, the optimization problem is formulated as

$$\underset{z}{\text{maximize}} \quad \sum_{s\in\mathcal{S}}\sum_{u\in\mathcal{U}} z_s r_u^l(t_s) \tag{11a}$$

$$\text{subject to} \quad \sum_{s\in\mathcal{S}}\sum_{n\in\mathcal{N}} (1 - z_s) r_n^w(t_s) \geq \gamma, \tag{11b}$$

$$z_s \in \{0, 1\} \;\; \forall s \in \mathcal{S}. \tag{11c}$$

Here, constraint (11b) protects the WiFi users and ensures that the sum-data rate of all WiFi users is higher than a predefined threshold γ.

IV. Proposed Hopfield Neural Networks (HNNs) Based Approach

The problem (11) is a mixed-integer nonlinear programming (MINLP) which is difficult to obtain a closed form solution. Thus, we model the problem as a HNN to find the optimum solution for the variables z_s. We represent each time (t_s) as a neuron in HNN as shown in Fig. 3. Here, firing neurons, i.e. neurons with state 1, correspond to *ON slots* of which LTE-U BS can transmit over it while neurons with state 0 correspond to *OFF slots* of which LTE-U BS stops its transmission and this allows the WiFi network to transmit. Accordingly, a HNN with S neurons is considered, i.e. the number of neurons of the HNN equals to the number of time slots S.

We modify the optimization problem (11) and rewrite it in the HNN's energy function form. Therefore, we can calculate the weight matrix and thresholds by matching $E(y)$ and the modified optimization problem. The optimization problem (11) can be modified by pushing the constraint (11b) into the objective function and write it in a minimization form as follows

$$\underset{z}{\text{minimize}} \quad -\sum_{s\in\mathcal{S}}\sum_{u\in\mathcal{U}} z_s r_u^l - \rho \sum_{s\in\mathcal{S}}\sum_{n\in\mathcal{N}} (1 - z_s) r_n^w \tag{12a}$$

$$\text{subject to} \quad z_s \in \{0, 1\} \;\; \forall s \in \mathcal{S}, \tag{12b}$$

where $0 \leq \rho \leq 1$ is the weight that controls the preference of WiFi data rates. The above objective function can be modified and written as follows

$$f(z) = -\sum_{s\in\mathcal{S}}\sum_{u\in\mathcal{U}} z_s r_u^l - \rho\sum_{s\in\mathcal{S}}\sum_{n\in\mathcal{N}}(1-z_s)r_n^w \tag{13}$$
$$= -\sum_{s\in\mathcal{S}}\sum_{k\in\mathcal{S}}\sum_{u\in\mathcal{U}} \xi_{sk} r_u^l z_s z_k - \rho\sum_{s\in\mathcal{S}}\sum_{n\in\mathcal{N}} r_n^w(1-z_s)$$
$$= -\sum_{s\in\mathcal{S}}\sum_{k\in\mathcal{S}}\sum_{u\in\mathcal{U}} \xi_{sk} r_u^l z_s z_k + \rho\sum_{s\in\mathcal{S}}\sum_{n\in\mathcal{N}} r_n^w z_s$$
$$- \rho\sum_{s\in\mathcal{S}}\sum_{n\in\mathcal{N}} r_n^w$$

where δ is defined as follows:

$$\xi_{sk} = \begin{cases} 1, & \text{if } s = k \\ 0, & \text{otherwise} \end{cases} \tag{14}$$

We can find the weights and thresholds by comparing equation (13) to equation (2) as follows

$$w_{sk} = 2\sum_{u\in\mathcal{U}} \xi_{sk} r_u^l \tag{15}$$

$$\theta_s = \rho(1-S)\sum_{n\in\mathcal{N}} r_n^w \tag{16}$$

As illustrated in algorithm 1, we first generate a random states for all neurons and calculate the energy function, weight matrix, and thresholds from equations (15), (16), and (2) respectively. For each iteration, we randomly select a neuron s and update it based on the updating rule in (1). Finally, we calculate a new value for $E(z)$ and compare it to the previous one. These steps are repeated until the convergence of $E(z)$.

Algorithm 1: HNNs based LTE-U/WiFi Scheduler

Input: $\mathcal{U}$, $\mathcal{N}$, Network parameters.
Output: Neurons state z.
Start:
Generate an initial state z for all neurons randomly
Calculate r_u^l and r_n^w
$W_{sk} = 2\sum_u \xi_{sk} r_u^l$
$\theta_s = \rho(1-S)\sum_n r_n^w$
$E(z) = \frac{-1}{2}\sum_s\sum_k w_{sk} z_s z_k + \sum_s \theta_s z_s$
repeat
  Select a neuron s randomly
  if $\sum_k w_{sk} z_k \geq \theta_s$ **then**
    $z_s = 1$
  end
  else
    $z_s = 0$
  end
  $E(z) = \frac{-1}{2}\sum_s\sum_k w_{sk} z_s z_k + \sum_s \theta_s z_s$
until *($E(z)$ converges or the maximum number of iterations is reached)*
Wait t_w.
Goto *Start*.

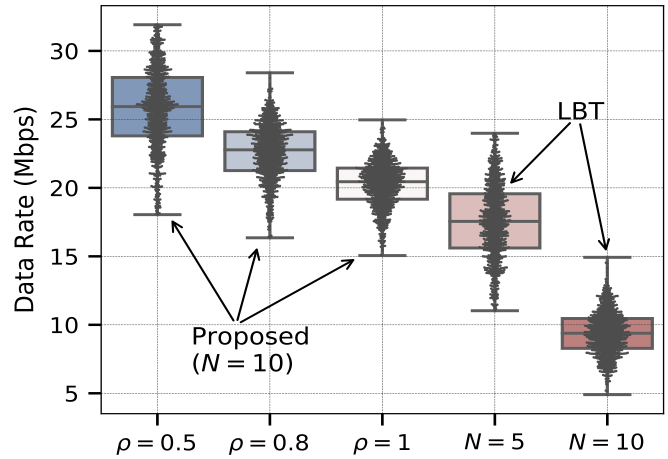

Fig. 4: A comparison between the proposed HNN based algorithm and the LBT mechanism in term of the LTE-U data rate

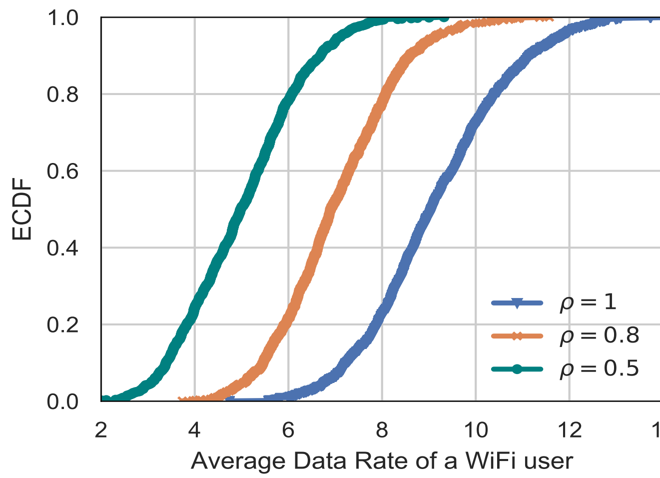

Fig. 5: The Data rate per WiFi user (Mbps) for different values of ρ

V. Performance Evaluation

In this section, we evaluate the proposed HHN based coexistence mechanism and compare it to the LBT technique. A number of cellular users is distributed randomly and connected to the LTE-U BS. Moreover, We distribute a number of WiFi users randomly in the WAP's coverage area. The unlicensed band is divided into 100 RBs with 180 KHz frequency width of each RB. Here, we consider that RBs are allocated equally to LTE-U users.

We study the the proposed coexistence algorithm for different number of WiFi users, and different values of ρ. Moreover, we compare the proposed approach to the LBT mechanism.

Fig. 4 compares the proposed HNN based coexistence mechanism to the LBT algorithm. We run the LBT algorithm with different number of WiFi users since the number of users directly affects its performance. The proposed HNN based approach gives average data rate around $26Mbps$ for $\rho = 0.5$ and around $20Mbps$ for $\rho = 1$. However, the LBT algorithm gives data rate around $17Mbps$ at $N = 5$ and reduces it exponentially to around $8Mbps$ when increasing the number of WiFi users to 10. Hence, the LBT algorithm cannot work efficiently with a large number of users. Contrarily, the proposed mechanism gives better results for the LTE-U network even if the number of WiFi users are increased, i.e., the number of WiFi users is 10 in the proposed mechanism results.

Fig. 5 shows the per user data rate of the WiFi network for different values of ρ. As shown in Fig. 5, increasing the value of ρ increases the data rate and this means that we can control the impact on the WiFi network by adjusting the parameter ρ. As shown in Fig. 5, the median of WiFi data rate is around $10Mbps$ in case of $\rho = 1$ where it is around $5Mbps$ in case of $\rho = 0.5$.

VI. Conclusions

In this work, we have proposed a neural networks based model for the coexistence problem of an LTE-U BS in the unlicensed band alongside with a WAP. We have formulate the problem as an optimization problem that aims to achieve a fair coexistence considering both the LTE-U data rate and WiFi QoS. Furthermore, we modeled the problem as a HNN, where time slots are represented as neurons and the formulated problem is rewritten in same form of the HNN's energy function. Simulation results showed that the proposed mechanism allows the LTE-U network to work efficiently in the unlicensed spectrum alongside with teh WAP. In addition, the proposed algorithm allows us to control the impact on the WiFi network by adjusting the WiFi network's weight value. As a future work, we will extend the proposed approach to model a system with multiple LTE-U BSs and multiple WAPs. Here, we will leverage the 2-Dimensions HNNs (2D-HNNs) to model such complicated system.

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