PCF-Based LTE Wi-Fi Aggregation for Coordinating and Offloading the Cellular Traffic to D2D Network

Bushra Ismaiel, *Student Member IEEE*, Mehran Abolhasan, *Senior Member, IEEE*, Wei Ni, *Senior Member, IEEE*, David Smith, *Member, IEEE*, Daniel Franklin, *Member, IEEE*, Eryk Dutkiewicz, *Member, IEEE*, Marwan Krunz, *Fellow, IEEE* and Abbas Jamalipour, *Fellow, IEEE*

***Abstract*—Device-to-Device (D2D) communication is a promising technology towards 5G networks. D2D communication can offload traffic using licensed/unlicensed band by establishing a direct communication between two users without traversing the base station (BS) or core network. However, one of the major challenges of D2D communication is resource allocation and guaranteeing Quality-of-Service (QoS). In this paper, we establish an optimal queuing scheduling and resource allocation problem for three-tier heterogeneous network based on LTE Wi-Fi aggregation (LWA), to offload voice/multimedia traffic from licensed band to unlicensed band using Scalable MAC Protocol (SC-MP) under various static delay constraints. The access mechanism used for Wi-Fi in SC-MP is Point Coordination Function (PCF), which further offloads the multimedia traffic using D2D communication in unlicensed band. Resource allocation and optimal joint queuing scheduling problems are formulated with diverse QoS guarantee between licensed and unlicensed band to minimize the bandwidth of licensed band. Furthermore, an iterative algorithm is proposed to express the non-convex problem as series of sub-problems based on Block Coordinate Descent (BCD) and difference of two convex functions (D.C) program. We have simulated the proposed scheme using two scenarios; voice traffic using licensed band and voice traffic using both licensed and unlicensed band whereas, multimedia traffic uses unlicensed band for both scenarios. The simulation results show that both the schemes perform better than the existing scheme and scenario 2 outperforms scenario 1.**

***Index Terms*—Device-to-Device communication, Effective capacity, Wireless local area network (WLAN), Long term evolution (LTE) network, Resource allocation, Quality-of-Service (QoS)**

I. Introduction

The rapid growth in demand for wireless devices has accelerated the development of next-generation wireless networks, namely, 5G. In 5G, it is proposed to use a wider range of frequencies and spectrum to solve the capacity problem. In a dense heterogeneous network environment, the licensed spectrum is easily congested due to limited resources. This has motivated the operators to exploit the potential use of the available unlicensed spectrum. Recently, several new schemes have been proposed to overcome the coverage and congestion problems which include; deployment of small cells (Femto, Pico), cognitive radio, LTE unlicensed (LTE-U), LTE licensed assisted access (LTE-LAA) and LTE Wi-Fi aggregation (LWA).

Joint deployment of cellular networks and wireless Local area networks (WLAN) is more attractive to the operators as it utilizes both licensed and unlicensed band. There are several advantages of joint deployment such as; it is cost-effective, WLAN works with less complex protocol as compared with the cellular network (LTE, LTE-A), better spatial reuse and it enabling access to local services utilizing unlicensed band [1]. Currently, LTE-U/LTE-LAA has been the center of attraction now adays but the real challenge for LTE-U/LTE-LAA is the contention problem with the Wi-Fi users, as the greater preference is given to LTE-U/LTE-LAA users, which will enable them dominate the spectrum [2], [3]. LWA does not require another protocol like CSAT/LBT, but rather utilizes the same existing Wi-Fi protocol and it transmits LTE traffic through Wi-Fi access point (AP) associated with LWA base stations [2]. LWA has several advantages that include; improved quality-of-service(QoS), cost effective, and increase system capacity. Furthermore, joint operation between WLAN and LTE is simple in LWA as LTE operates using LTE protocol and Wi-Fi operates using Wi-Fi traditional protocol [4].

D2D communication is another technology that can increase the capacity and coverage of the wireless networks by enabling immediate communication between the users. D2D communication allows two proximity users to perform direct data transmissions between each other with little or no involvement of a base station (BS). D2D technology, has also been proposed as an effective solution for efficiently utilizing the radio resources, hence increasing the spectral efficiency. Furthermore, it eases the core network data processing loads by performing traffic offloading [5]. D2D communication will be an integral part of 5G technology because of its particular features; increase in spectral efficiency, capacity gain, and lower end-to-end delay [6], [7]. Resource allocation is the key

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B. Ismaiel, M. Abolhasan, D. Franklin and Eryk Dutkiewicz are associated with the School of Electrical and Data Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia. (e-mail: bushra.ismaiel@student.uts.edu.au; mehran.abolhasan@uts.edu.au; daniel.franklin@uts.edu.au; eryk.dutkiewicz@uts.edu.au)

W. Ni and D. Smith are the Senior Research Scientist and associated with Data61, CSIRO, Clayton, VIC 3169, Australia. (e-mail: Wei.Ni@data61.csiro.au; david.smith@data61.csiro.au).

Marwan Krunz is the Professor in the Department of Electrical and Computer Engineering at the University of Arizona (UA), ECE Bldg., Rm. 365, 1230 East Speedway Blvd., Department of Electrical and Computer Engineering University of Arizona, Tucson, AZ 85721. (e-mail: krunz@email.arizona.edu).

A.Jamalipour is a Professor and is associated with School of Electrical and Information Engineering, University of Sydney, Camperdown NSW 2006, Australia. (e-mail: a.jamalipour@ieee.org).

aspect in D2D communication, and most of the work has been done using cellular network [8].

Nowadays, there are high demands for video and multimedia content over cellular networks. Downloading similar videos can waste the spectrum resource. However, D2D communication can be significant in caching videos and sharing content [9]. D2D users can act cooperatively, form clusters and facilitate content dissemination [10], [11]. Service providers can exploit D2D communication to additionally offload traffic in a congested domain particularly utilizing unlicensed band.

The novelty of the paper is to investigate an optimal queue scheduling and resource allocation problem of diverse traffic in three-tier heterogeneous network with Wi-Fi access mechanism based on IEEE 802.11 PCF and further offloading multimedia files through D2D communication. There is an ongoing work [12], that proposes an optimal solution for offloading traffic using LWA. Our proposed scheme builds on and further extends the approach proposed in [7]. The diverse traffic; voice and multimedia, will be offloaded from licensed band to unlicensed band in three-tier network using IEEE 802.11 PCF as the access mechanism for Wi-Fi and further multimedia traffic is offloaded using D2D communication. Our key contributions can be summarized as:

- A three-tier network based on LWA technology is proposed to offload diverse traffic from licensed to unlicensed band with modification in resource allocation scheme based on IEEE 802.11 PCF to access Wi-Fi channels and further offload multimedia files through D2D communication. The optimal joint queue scheduling and resource allocation problem of three-tier network is formulated to minimize the bandwidth of licensed band by guaranteeing the QoS.
- A closed-form expression of effective capacity is derived using 6 state semi-Markovian model.
- An iterative algorithm is proposed to convexify the problem using generic block coordinated descent (BCD) and difference of convex functions (D.C) program.
- Simulation is performed using two scenarios of the proposed schemes; in the first scenario the voice traffic uses licensed band whereas multimedia traffic uses unlicensed band and in the second scenario half of the voice traffic goes through licensed band and other half of the traffic goes to unlicensed band along with the multimedia traffic. Our result proved that both scenarios perform better than SMS and scenario 2 outperforms scenario 1.

The paper is organized as follows. In Section II, foundation and related works are discussed and surveyed. In Section III, the system model is presented. In Section IV, the closed form expression for effective capacity of three-tier network is derived. In Section V, the optimal joint queue scheduling and resource allocation problems with the QoS guarantee between licensed and unlicensed band are formulated to minimize the usage of licensed bandwidth of three-tier heterogeneous network. An iterative algorithm is proposed based on BCD and DC programs to solve the problem. In Section VI, the simulation results are shown, and finally, conclusion is presented in Section VII.

II. Related Work

The performance characteristics of PCF has been extensively studied in [13]–[15]. The performance of video transmission using PCF mechanism is discussed in [16], [17].

In [18], a cooperative ARQ MAC protocol is proposed that is compatible to the legacy IEEE 802.11 DCF. It coordinates the transmissions among a set of relay nodes which act as helpers in a bidirectional communication. The maximization of the effective capacity with QoS and power constraints using DCF is proposed in [19].

The aggregation of LTE and Wi-Fi has recently drawn extensive attention. In [20], LWA analytical model was proposed using Markovian model. In [21], convex optimization technique was used to optimize the power of licensed band and time duration of the unlicensed band to maximize the total algorithmic utility of users. In [22], a linear program technique was used to optimize the licensed bandwidth allocation and rate allocation in the unlicensed band to maximize the overall throughput. In [23], a cross-system learning approach is proposed to optimize the power, cell range expansion bias, subband selection and traffic scheduling and the delay-tolerant traffic is steered to unlicensed band. The access mechanism used in Wi-Fi in [21]–[23] is DCF which is contrary to our work as we will be using PCF as an access mechanism and further offloading the traffic using D2D communication, which is very useful for the dense environment as assigning QoS.

Some related work have been focused on the QoS of the queues transmitted through a single interface. In [24], a semi-Markovian model was proposed for Wi-Fi based on distributed coordinated function (DCF) access channel mechanism. It provides for an asymptotically tight linkage between source characteristics, system resources, and QoS. In [25], a unified framework for LWA was proposed based on QoS class indicator, but there was no analytical model. A non-trivial effort would be required to extend these works to multiple heterogeneous interfaces, as proposed in this paper. In [26], Karush-Kuhn-Tucker technique was used to maximize the effective capacity of the mobile video traffic. In [27], [28], the effective capacity is focused on the modelling of rate fluctuations at the physical layer. In [12], author proposes to offload traffic from licensed band to unlicensed band using LWA technology under delay constraints and also derive effective capacity using semi-Markovian model. Our work differs from [12] as we will be introducing a three tier network to offload voice/multimedia traffic from licensed to unlicensed band with modification in resource allocation scheme based on IEEE 802.11 PCF to access Wi-Fi channels and further offload multimedia files through D2D communication. We can conclude that our proposed scheme is scalable and perform better with no contention problem in it.

To the best of our insight, no analytical work has been published until now for offloading traffic from LTE to Wi-Fi based on IEEE 802.11 PCF mechanism and further offloading multimedia traffic through D2D communication. This paper presents an analytical model for three-tier heterogeneous network using Scalable MAC protocol for Wi-Fi network, to evaluate an optimal joint queue scheduling and resource allocation problem under various static delay constraints. The simulation results illustrate that the proposed scheme has significant performance gain as compared to the state of art.

III. System Model

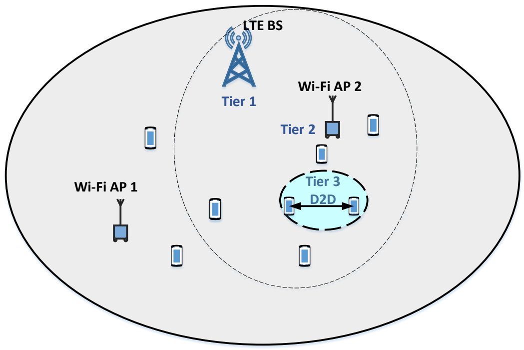

Fig. 1: Proposed Three-Tier Heterogeneous Network

Our proposed architecture builds on the LTE-Wi-Fi aggregation (LWA) technology with modification in resource allocation scheme based on IEEE 802.11 PCF to access WLAN channel and D2D communication integration. As the architecture is proposed for 5G, it is also assumed that Software Defined Network (SDN) is deployed at the core end so that the decisions made are structured, rapid and congestion controlled. SDN and routing protocol is out of the scope of our paper but for further understanding [29] and [30] can be referred. The Fig. 1, shows the architecture of proposed three-tier network.

We consider a macro LTE base station (BS) with an LTE air interface in the licensed band overlayed by a Wi-Fi base station (BS) with Wi-Fi air interface in the unlicensed band. We have also considered another Wi-Fi node operating in an unlicensed band within the coverage of three-tier network. Two frequency bands are considered; band a is the licensed bandwidth and band b is the unlicensed bandwidth. The total bandwidth is given as B_n where n = a, b. Both voice and multimedia traffic is taken into account and licensed and unlicensed bandwidth are further sub-divided. Let B_{av} and B_{am} be the licensed bandwidth for voice and multimedia and B_{bv} and B_{bm} be the unlicensed bandwidth for voice and multimedia. There are total K number of users, where $\gamma_{k,n}$ represent the signal-to-interference-noise ratio (SINR) of a user k in band n and $k = 1,\ldots,K$. The packets are delivered to the users either using licensed LTE air interface or using unlicensed Wi-Fi air interface.

The Wi-Fi users operating in the unlicensed band use Scalable MAC Protocol (SC-MP) based on point coordination function (PCF) to access the channel [31]. PCF consist of contention free period (CFP) and a contention period (CP) and works on a polling based mechanism. PCF has point coordinator (PC), which is located at a Wi-Fi Access Point (AP). During CFP the point coordinator (PC) creates a polling list and polls the node accordingly. PC ensures that the interval between two polling stations is not more than PCF inter-frame spacing (PIFS) [32]. The polling scheme used is the best signal-to-noise ratio (SINR) scheme. The advantage of best SINR polling scheme is that it will give better throughput with less delay. The PC creates a polling list based on best SINR polling scheme and poll the user accordingly. PC has to sense if the channel is idle for PCF inter-frame spacing (PIFS) period and then a beacon frame is transmitted at the start of CFP. PC polls the first user from the polling list and if the user has data to transmit, a time slot (TS) is allocated to that user. If the user does not have any data to transmit a null frame is transmitted. Similarly, all the users are polled accordingly from the polling list and if the cycle ends before all users are polled then in the next cycle PC will resume polling where the polling list ended.

We further apply D2D communication for caching video/multimedia files using CP in PCF [31]. When a user is polled by WLAN BS (WBS) and requests a video, WBS checks if any of the neighbouring user has downloaded the requested video. If the requested video is already downloaded by the neighbouring user, WBS will check the distance between the two users and if distance is less than the threshold value it will allow D2D communication between the two users by assigning a free channel for a specific time period. If the video is not downloaded, WBS assigns a time slot to the user to download the video. Once the video is downloaded, it will be stored in the cache memory of WBS with the location information of the user. If downloaded video is not requested by any other user for a certain time, WBS deletes the video from the cache memory as it will save the storage space [31].

We assume Rayleigh block flat-fading channels in both licensed and unlicensed bands. The packets arriving at the scheduler for the user k can be scheduled to proceed using either licensed LTE air interface or unlicensed Wi-Fi air interface. Two transmit queues are formed for the two air interface as shown in the Fig. 2. A binary variable $y_{n,k}$ is defined to select the band for the packets. The bandwidth allocated to a user with binary variable $y_{n,k}$ is $\alpha_{n,k}$. The channel remains unchanged during a time frame T, but can vary independently across different time frames.

The QoS exponent θ_k is the QoS packets intended for the user k. The larger the value of θ_k, the more stringent is the QoS and the smaller the value of θ_k the more loose is the QoS. If both air interfaces are selected, we propose to decouple θ_k between the two interfaces. QoS exponent of user k in band n is denoted as $\theta_{n,k}$. We propose to precisely design the binary variable $y_{n,k}$, bandwidth $\alpha_{n,k}$ and QoS $\theta_{n,k}$ such that the maximum number of packets can be delivered without compromising θ_k for all the users.

We also propose that each user n requires a minimum data rate of R_k, a delay bound of D^k_{th} and the maximum probability threshold of the delay bound being violated is P^k_{th}. The effective capacity $C_{n,k}(\theta_{n,k})$, can be defined to the maximum consistent arrival rate at the input of the transmit queue for user k in band n, as given by [27], [33], [34];

$$C_{n,k}(\theta_{n,k}) = -\lim_{t\to\infty} \frac{1}{\theta_{n,k}t} \log(\mathbf{E}\{e^{-\theta_{n,k}S_{n,k}(t)}\}) \quad (1)$$

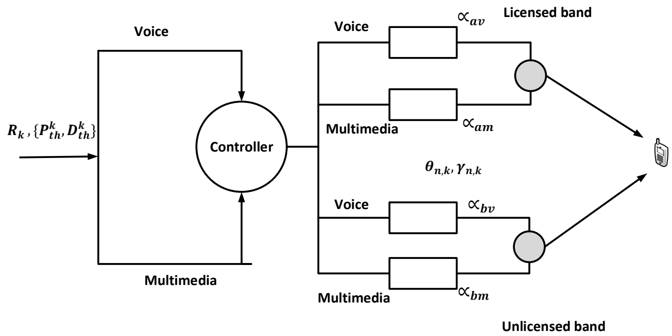

Fig. 2: Queuing Model Of Three-Tier Network

where $S_{n,k}(t)$ is the number of bits successfully delivered to Wi-Fi user k during (0,t] and $\mathbf{E}\{.\}$ denotes expectation.

According to the effective capacity theory [26], the delay-bound violation probability of the transmit queue in each individual band can be approximated as;

$$Pr\{D > D_{th}^{k}\} \approx e^{-\theta_{n,k} C_{n,k}(\theta_{n,k}) D_{th}^{n}}, \forall k \in K, \forall n \in N \quad (2)$$

Overall, the delay-bound violation probability needs to satisfy [26];

$$\frac{\sum_{n \in N} y_{n,k} e^{-\theta_{n,k} C_{n,k}(\theta_{n,k}) D_{th}^{k}} C_{n,k}(\theta_{n,k})}{\sum_{n \in N} y_{n,k} C_{n,k}(\theta_{n,k})} \leq P_{th}^{k}, \forall k \in K, \quad (3)$$

where $\sum_{n \in N} y_{n,k} C_{n,k}(\theta_{n,k})$ is the total number of packets delivered to user and $\sum_{n \in N} y_{n,k} e^{-\theta_{n,k} C_{n,k}(\theta_{n,k}) D_{th}^{k}} C_{n,k}(\theta_{m,n})$ accounts for the total number of packets delivered to user k before the delay bound through the two bands.

IV. Effective Capacity of LTE and Scalable MAC Protocol (SC-MP)

In this section we will discuss the effective capacity of SC-MP operating in unlicensed band and LTE operating in licensed band, while preserving the QoS.

A. *Effective Capacity Of SC-MP in Unlicensed Band*

A semi-Markovian model is used to derive the effective capacity of SC-MP of K number of users with total $3K$ states with each user having 3 states. In Fig. 3, a semi-Markovian model is shown with 2 users having 6 states in total.

Two types of traffic is considered in the framework for the allocation of a time slot; voice and video/multimedia. Moreover, D2D communication is also applied to video/multimedia traffic for offloading the traffic. We have assumed that duration of voice traffic in a time slot is random and the voice duration can vary for every user depending on the number of packets in the buffer. Similarly, for multimedia traffic either the user is allocated a time slot to transmit or the user will be allowed for D2D communication. The probability that a user has data in the buffer is P, and 1-P is the probability that there is no data in the buffer. The probability P can either be a voice traffic or a video/multimedia traffic.

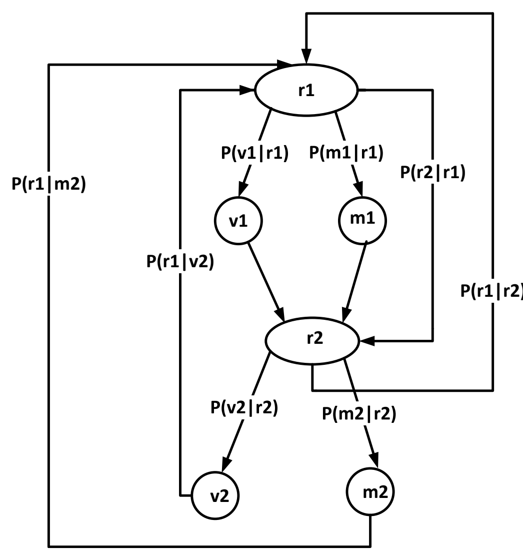

Fig. 3: SC-MP Semi-Markovian Model

$$P = P_V \text{ or } P = P_M \quad (4)$$

where P_V is the probability of voice traffic and P_M is the probability of video/multimedia traffic. Two types of channel condition are used in modelling the SC-MP; J and E. E is the channel condition that should be satisfied for the allocation of the time slot for voice and video/multimedia traffic. Whereas, J is the channel condition that should be satisfied for D2D communication between two users. D2D communication will be allowed if the video requested by the user is already downloaded by the neighbouring user/users and is in the cache memory of the AP and satisfies the channel condition J. The probabilities are defined as, P_{ND}= Probability that video requested is not downloaded by any neighbouring users, P_S= Probability that channel condition E is not satisfied and P_D= Probability that channel condition J is not satisfied.

Each user has 3 unique states: r_k = polling state of a Wi-Fi user, v_k = time slot allocation for a Wi-Fi user having voice traffic and satisfying the channel condition E, m_k = a time slot is allocated for video/multimedia traffic to a Wi-Fi user after satisfying the channel condition E or allow D2D communication to a Wi-Fi user if the neighbour has already downloaded the video/multimedia file and satisfy the channel condition J, where $k = 1, \ldots, K$.

The transition probability from polling state r_1 to v_1 for user$_1$ is given as

$$P_{A1} = P(v_1|r_1) = P_{V1}(1 - P_{S1}) \tag{5}$$

Similarly, the transition probability for user$_2$ is given as

$$P_{A2} = P(v_2|r_2) = P_{V2}(1 - P_{S2}) \tag{6}$$

where P_{V1} and P_{V2} are the probabilities of voice traffic for user$_1$ and user$_2$. $1\text{-}P_{S1}$ and $1\text{-}P_{S2}$ are the probabilities that satisfies the channel condition E for time slot allocation for user$_1$ and user$_2$ for voice and video/multimedia traffic.
The transition probability from r_1 to m_1 is given as

$$\begin{aligned} P_{F1} = P(m_1|r_1) = P_{M1}(1 - P_{S1}) \\ +(P_{M1})(P_{S1})[1 - (P_{ND1} \\ +((1 - P_{ND1})P_{D1})^{N_n})] \end{aligned} \tag{7}$$

Similarly, for user$_2$ the transition probability is given as

$$\begin{aligned} P_{F2} = P(m_2|r_2) = P_{M2}(1 - P_{S2}) \\ +(P_{M2})(P_{S2})[1 - (P_{ND2} \\ +((1 - P_{ND2})P_{D2})^{N_n})] \end{aligned} \tag{8}$$

where P_{M1} and P_{M2} are the probabilities of video/multimedia traffic for user$_1$ and user$_2$. $1\text{-}P_{S1}$ and $1\text{-}P_{S2}$ are the probabilities that satisfies the channel condition E for time slot allocation for user$_1$ and user$_2$, N_n is the total number of neighbours that downloaded the video, P_{ND1} and P_{ND2} are the probabilities that video requested by user$_1$ and user$_2$ is not downloaded by any neighbouring users and P_{D1} and P_{D2} are the probabilities that channel condition J is not satisfied for D2D communication for user$_1$ and user$_2$. The transition probability for polling state r_1 to polling state r_2 is given as

$$P_{E1} = 1 - P_{A1} - P_{F1} \tag{9}$$

$$P_{E2} = 1 - P_{A2} - P_{F2} \tag{10}$$

The transition probability for all other states are 1. The state transition probabilities generate the transition matrix **Q**, using semi-Markovian model for 2 users and is given as

$$\mathbf{Q} = \begin{bmatrix} 0 & P_{A1} & P_{F1} & P_{E1} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ P_{E2} & 0 & 0 & 0 & P_{A2} & P_{F2} \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

The duration of both states r_1 and r_2 is T_{r_1} and T_{r_2} and is constant for both users. The duration for v_1 and v_2 is random and denoted by T_{v_1} and T_{v_2}, which depend on the number of packets in the buffer. The duration for m_1 and m_2 is random and is denoted by T_{m1} and T_{m2}, it can either transmit video/multimedia traffic through time slot or can allow D2D communication between users depending on the channel condition and neighbouring downloaded traffic.

The moment generating functions (MGF) of T_{r1}, T_{v1}, T_{m1}, T_{r2}, T_{v2}, *and* T_{m2} are $M_1(t)=e^{tTr1}$, $M_2(t)=\Sigma e^{tTv1}P_{A1}$, $M_3(t)=\Sigma e^{tTm1}P_{F1}$, $M_4(t)=e^{tTr2}$, $M_5(t)=\Sigma e^{tTv2}P_{A2}$, *and* $M_6(t)=\Sigma e^{tTm2}P_{F2}$.

We define two auxiliary variables, s and u, with reference to [24], [35]. We now create a diagonal matrix Γ(s,u). The diagonal elements of Γ(s,u) are the MGFs of the six state semi-Markovian model and is given in (12). The matrix $\mathbf{H}(s,u)$ is a non-negative irreducible matrix, as it cannot be arranged to upper triangular matrix, e.g, by using the Gaussian-Newton Method [36]. The spectral radius of $\mathbf{H}(s,u)$, denoted by $\phi(s,u)=\rho(\boldsymbol{H}(s,u))$ is a simple eigenvalue of $\mathbf{H}(s,u)$ and $\rho(.)$ represents the spectra radius.
We can write for each permissible pair of s and u $\mathbf{H}(s,u)=\mathbf{\Gamma}(s,u)\boldsymbol{Q}$ and is given in (13).

With reference to [35], the effective capacity $C = \frac{u(s)}{s}$, when $\phi(s,u(s))$ = 1 and θ = -s.

As the result, the effective capacity C can be evaluated by solving $\phi(-\theta,-\theta C)=1$ for $\theta>0$ [24], [35]. Meanwhile, $\phi(-\theta,-\theta C)$ is the eigenvalue of $(\boldsymbol{H}(-\theta,-\theta C))$, we have (14), where **I** is the identity matrix and $|.|$ is the determinant of the matrix. The determinant is given in (15) where,

$$\begin{aligned} X = M_2(-R\theta + \theta C)P_{A1}P_{E2} + M_3(-R\theta + \theta C)P_{F1}P_{E2} + \\ M_5(-R\theta + \theta C)P_{E1}P_{A2} + M_6(-R\theta + \theta C)P_{E1}P_{F2} \end{aligned}$$

$$\begin{aligned} Y = P_{A1}P_{A2}M_2(-R\theta + \theta C)M_5(-R\theta + \theta C) + P_{A1}P_{F2} \\ M_2(-R\theta + \theta C)M_6(-R\theta + \theta C) + P_{A2}P_{F1} \\ M_3(-R\theta + \theta C)M_5(-R\theta + \theta C) + P_{F2}P_{F1} \\ M_3(-R\theta + \theta C)M_6(-R\theta + \theta C) \end{aligned}$$

We substitute the λ = $\phi(-\theta,-\theta C)$ = 1 in (15).

Substituting the value of X and Y and solving (15) through the Matlab, the closed form expression of effective capacity for voice and multimedia of 2 users of SC-MP in unlicensed band is given as;

$$C_{bv}(\alpha_{bv}, \theta_b) = \frac{z}{\theta_b} + \alpha_{bv} \log(1 + \overline{\gamma_b}) \tag{16}$$

$$C_{bm}(\alpha_{bm}, \theta_b) = \frac{z}{\theta_b} + \alpha_{bm} \log(1 + \overline{\gamma_b}) \tag{17}$$

where $\overline{\gamma_b}$ is signal-to-interference-noise ratio (SINR) of a user in unlicensed band and z is a constant value and varies with the value of probabilities defined, that is; P_V, P_M, P_D and P_{ND} for every user. We can be calculate the value of z by inserting the values of P_V, P_M, P_D and P_{ND} in equation (15).

B. Effective Capacity of LTE in Licensed Band

The effective capacity of LTE in the licensed band of user k is given by [12], [37];

$$C_{a,k}(\alpha_{a,k}, \theta_{a,k}) = -\frac{1}{\theta_{a,k}T} \log(\mathbb{E}_\gamma\{e^{-\theta_{a,k}\alpha_{a,k}T\log_2(1+\overline{\gamma}_{a,k})}\}) \tag{18}$$

$$\mathbf{\Gamma}(s,u)=\begin{bmatrix}M_1(-u)&0&0&0&0&0\\0&M_2(Rs-u)&0&0&0&0\\0&0&M_3(Rs-u)&0&0&0\\0&0&0&M_4(-u)&0&0\\0&0&0&0&M_5(Rs-u)&0\\0&0&0&0&0&M_6(Rs-u)\end{bmatrix} \tag{12}$$

$$\mathbf{H}(s,u)=\begin{bmatrix}0&M_1(-u)P_{A1}&M_1(-u)P_{F1}&M_1(-u)P_{E1}&0&0\\0&0&0&M_2(Rs-u)&0&0\\0&0&0&M_3(Rs-u)&0&0\\M_4(-u)P_{E2}&0&0&0&M_4(-u)P_{A2}&M_4(-u)P_{F2}\\M_5(Rs-u)&0&0&0&0&0\\M_6(Rs-u)&0&0&0&0&0\end{bmatrix} \tag{13}$$

$|\mathbf{H}(-\theta,-\theta C)-\phi(-\theta,-\theta C)\mathbf{I}|$ =

$$\begin{vmatrix}-\phi(-\theta,-\theta C)&M_1(-u)P_{A1}&M_1(-u)P_{F1}&M_1(-u)P_{E1}&0&0\\0&-\phi(-\theta,-\theta C)&0&M_2(Rs-u)&0&0\\0&0&-\phi(-\theta,-\theta C)&M_3(Rs-u)&0&0\\M_4(-u)P_{E2}&0&0&-\phi(-\theta,-\theta C)&M_4(-u)P_{A2}&M_4(-u)P_{F2}\\M_5(Rs-u)&0&0&0&-\phi(-\theta,-\theta C)&0\\M_6(Rs-u)&0&0&0&0&-\phi(-\theta,-\theta C)\end{vmatrix} \tag{14}$$

$$=\phi(-\theta,-\theta C)^6-\phi(-\theta,-\theta C)^4P_{E1}P_{E2}M_1(\theta C)M_4(\theta C)-\phi(-\theta,-\theta C)^3M_1(\theta C)M_4(\theta C)X-\phi(-\theta,-\theta C)^2 M_1(\theta C)M_4(\theta C)Y \tag{15}$$

where $\overline{\gamma}_{a,k}$ is the signal-to-interference-noise ratio (SINR) of user *k* in licensed band.

The closed form expression of effective capacity in (18) for voice and multimedia can be written as:

$$C_{av,k}(\alpha_{av,k},\theta_{a,k}) = -\frac{1}{\theta_{a,k}T}\log(\mathbb{E}_\gamma\{e^{-\theta_{a,k}\alpha_{av,k}T\log_2(1+\overline{\gamma}_{a,k})}\}) \tag{19}$$

$$C_{am,k}(\alpha_{am,k},\theta_{a,k}) = -\frac{1}{\theta_{a,k}T}\log(\mathbb{E}_\gamma\{e^{-\theta_{a,k}\alpha_{am,k}T\log_2(1+\overline{\gamma}_{a,k})}\}) \tag{20}$$

where $C_{av,k}(\alpha_{av,k},\theta_{a,k})$ is the effective capacity of voice in licensed band and $C_{am,k}(\alpha_{am,k},\theta_{a,k})$ is the effective capacity in of multimedia in licensed band.

V. Minimizing the Bandwidth Of Licensed Band

The important objective of this section is to minimize the requirement of licensed bandwidth in three-tier heterogeneous network while guaranteeing the QoS for all users. For current problem formulation, we have assumed that voice traffic uses both licensed and unlicensed band, whereas multimedia traffic goes through the unlicensed band to minimize the usage of licensed band. In next Section VI, we compare this scenario with another scenario where voice traffic goes to licensed band and multimedia traffic goes through unlicensed band and observe their performance.

According [12], we can also formulate the problem in our scheme as

$$\mathbf{P1}: \underset{\alpha_{n,k},\theta_{n,k},y_{n,k}}{minimize} \sum_{k\in K} y_{n,k}\alpha_{n,k} \tag{21a}$$

$$s.t., \frac{\sum_{n\in N} y_{n,k}e^{-\theta_{n,k}C_{n,k}(\theta_{n,k})D^k_{th}}C_{n,k}(\theta_{n,k})}{\sum_{n\in N} y_{n,k}C_{n,k}(\theta_{n,k})} \leq P^k_{th}, \forall k\in K \tag{21b}$$

$$\sum_{k\in K} y_{b,k}\alpha_{b,k} \leq B_b \tag{21c}$$

$$\sum_{n\in N} y_{n,k}C_{n,k}(\alpha_{n,k},\theta_{n,k}) \geq R_k, \forall k\in K \tag{21d}$$

$$y_{n,k}=0,1,\forall k\in K,\forall n\in N \tag{21e}$$

$$\alpha_{n,k}\geq 0, \theta_{n,k}\geq 0, \forall k\in N, \forall n\in N \tag{21f}$$

where (21b) describes to meet the requirement of QoS of user *k*, (21c) states the total unlicensed bandwidth that should not exceed B_b, (21d) represents the minimum data rate of the user *k*, , (21e), and (21f) are the generic restraints to specify the problem.

It can be observed that from **P1**, $e^{-\theta_{n,k}C_{n,k}D^k_{th}}$ and $y_{n,k}C_{n,k}$ are coupled and the effective capacity in (21d) is not joint convex on $\alpha_{n,k}$ and $\theta_{n,k}$. As $y_{n,k}$ being a binary variable and according to [12], it is said that

$$y_{n,k}C_{n,k}(\alpha_{n,k},\theta_{n,k}) = C_{n,k}(y_{n,k}\alpha_{n,k},\theta_{n,k}) \tag{22}$$

By using the inequality [38];

$$0 \le \alpha_{n,k} \le y_{n,k}\chi \tag{23}$$

where χ is a predefined constant. If both the licensed and unlicensed bands are selected to transmit the packets (21d) can be rewritten as

$$\sum_{n\in N} e^{-\theta_{n,k}C_{n,k}(\theta_{n,k})D^k_{th}} C_{n,k} \le P^k_{th}\sum_{n\in N} C_{n,k} \tag{24}$$

Using Chebyshev's sum inequality [39], (21d) can be written as

$$\frac{1}{|N|}\sum_{n\in N} e^{-\theta_{n,k}C_{n,k}(\theta_{n,k})D^k_{th}} \sum_{n\in N} C_{n,k} \le P^k_{th}\sum_{n\in N} C_{n,k} \tag{25}$$

where $|N|$ stands for cardinality. If a packet is transmitted to user *k* in band *n* the (21b) can be rewritten as ;

$$e^{-\theta_{n,k}C_{n,k}(\theta_{n,k})D^k_{th}} \le P^k_{th} \tag{26}$$

Combining (25) and (26), (21b) can be rewritten as

$$\sum_{n\in N} e^{-\theta_{n,k}C_{n,k}(\theta_{n,k})D^k_{th}} - 1 + y_{n,k} \le P^k_{th}\sum_{n\in N} y_{n,k} \tag{27}$$

The (21e), can be relaxed as the intersection of the following region [38];

$$0 \le y_{n,k} \le 1, \forall k \in K, \forall n \in N \tag{28}$$

$$\sum_{n\in N}\sum_{k\in K}(y_{n,k} - (y_{n,k})^2) \tag{29}$$

We state two variables for simplification; $\omega_{n,k} = \alpha_{n,k}\theta_{n,k}$ and $\beta_{n,k} = \frac{1}{\theta_{n,k}}$, where $\alpha_{n,k} = \omega_{n,k}\beta_{n,k}$. The effective capacity of SC-MP and licensed band in (16), (17), and (19) can be rewritten in terms of auxiliary variables as

$$C_{av,k}(\omega_{av,k}, \beta_{a,k}) = -\frac{\beta_{a,k}}{T} log(\mathbb{E}_\gamma\{e^{-\omega_{av,k}Tlog_2(1+\gamma_a)}\}) \tag{30}$$

$$C_{bv}(\alpha_{bv}, \beta_b) = z\beta_b + \omega_{bv}\beta_b log_2(1+\gamma_b) \tag{31}$$

$$C_{bm}(\alpha_{bm}, \beta_b) = z\beta_b + \omega_{bm}\beta_b log_2(1+\gamma_b) \tag{32}$$

Using (30), (31) and (32), (27) can be rewritten as

$$e^{\frac{log(\mathbb{E}_\gamma\{e^{-\omega_{av,k}Tlog_2(1+\gamma_a)}\})}{T}D^k_{th}} + e^{-(2z+\omega_{bv}\beta_b log_2(1+\gamma_b)+\omega_{bm}\beta_b log_2(1+\gamma_b)D^k_{th}} - 2 + \sum_{n\in N} y_{n,k} \le P^k_{th}\sum_{n\in N} y_{n,k}, \forall k \in K \tag{33}$$

As an outcome and according to [12], **P1** can be simplified to be a continuous problem and can be written as

$$\textbf{P2}: \underset{\{\omega_{n,k}\},\{\beta_{n,k}\},\{y_{n,k}\}}{minimize} \sum_{k\in K}\omega_{a,k}\beta_{a,k} \tag{34a}$$

$$e^{\frac{log(\mathbb{E}_\gamma\{e^{-\omega_{av,k}Tlog_2(1+\gamma_a)}\})}{T}D^k_{th}} + e^{-(2z+\omega_{bv}\beta_b log_2(1+\gamma_b)+\omega_{bm}\beta_b log_2(1+\gamma_b)D^k_{th}} - 2 + \sum_{n\in N} y_{n,k} \le P^k_{th}\sum_{n\in N} y_{n,k}, \forall k \in K \tag{34b}$$

$$\sum_{k\in K}(\omega_{bv,k} + \omega_{bm,k})\beta_{b,k} \le B_b \tag{34c}$$

$$s.t, \sum_{n\in N} C_{n,k}(\omega_{n,k}, \beta_{n,k}) \ge R_k, \forall k \in K \tag{34d}$$

$$\sum_{n\in N} y_{n,k} \ge 1, \forall k \in K \tag{34e}$$

$$\sum_{n\in N}\sum_{k\in K}(y_{n,k} - (y_{n,k})^2) \tag{34f}$$

$$\omega_{n,k} \ge 0, \beta_{n,k} \ge 0, 0 \le y_{n,k} \le 1, \forall n \in N, \forall k \in K \tag{34g}$$

$$0 \le \omega_{a,n}\beta_{a,n} \le y_{n,k}\chi, \forall k \in K, \forall n \in N \tag{34h}$$

As (34a), (34c), and (34d) are affine, therefore **P2** is linear on $\{\beta_{n,k}\}$.

Using difference of convex (DC) programming, **P2** can be reformulated using **P3**

$$\textbf{P3:} \underset{\{\omega_{n,k}\},\{y_{n,k}\}}{minimize} \sum_{k\in K}\omega_{a,k}\beta_{a,k} + \lambda\sum_{n\in N}\sum_{k\in K} y_{n,k} - \lambda\sum_{n\in N}\sum_{k\in K}(y_{n,k})^2, \tag{35}$$

$$s.t(34b) - (34d), (34f) - (34h), \tag{36}$$

where λ is a large penalty factor.

Let;

$$f_1(\omega_{n,k}, y_{n,k}) = \sum_{k\in K}\omega_{a,k}\beta_{a,k} + \lambda\sum_{n\in N}\sum_{k\in K} y_{n,k} \tag{37}$$

$$f_2(y_{n,k}) = \lambda\sum_{n\in N}\sum_{k\in K}(y_{n,k})^2 \tag{38}$$

$$f_1(\omega_{n,k}, y_{n,k}) - f_2(y_{n,k}) \tag{39}$$

where (39) is the difference of two convex functions. Hence, **P3** is a DC program in $\{\omega_{n,k}\}, \{y_{n,k}\}$.

According to [40], **P3** is equivalent to **P2** for large value of λ.

An algorithm is summarized based on a block coordinated descent (BCD) framework [41]. In the algorithm we initial number of users *K*, minimum data rate for each user R_k, signal-to-noise ratio of user $\gamma_{n,k}$, requirement for QoS, and total unlicensed bandwidth B_b. The algorithm consist of 2 loops. In the inner loop, given $\{\omega_{n,k}\}$ and $\{y_{n,k}\}$, **P2** is linear programming on $\{\beta_{n,k}\}$, and can be solved efficiently using interior-point method [42] and has a complexity of $O((2XY)^3(3Y + X + XY))$. In the outer loop, given $\{\beta_{n,k}\}$, **P2** is a DC program in $\{\omega_{n,k}, y_{n,k}\}$ and has a complexity of $O((XY)^3)$. The total complexity of algorithm 1 is $O((XY)^6(3Y + X + XY))$ based on [38].

VI. Simulation

In this section, we evaluate the performance of the proposed algorithm through simulation. There is one LTE Base station (LTE-BS) over-layed by WLAN BS (WBS). In our proposed scheme the WLAN BS contend the channel with the existing Wi-Fi systems before it can poll the users. We have also considered another Wi-Fi node operating in an unlicensed band within the coverage of proposed three-tier network. The channel model used for licensed and unlicensed bands are the ITU-UMi Models. We have assumed 10 users uniformly distributed and all have the same minimum data rate requirement and QoS requirement. We assumed the time frame length of LTE T = 1 ms.

We have used both voice and multimedia traffic, for voice we used persistent scheduling and for video we use adaptive scheduling. We have taken two different scenarios for our proposed scheme. In scenario 1, the voice traffic is assigned to the licensed band and the multimedia traffic is assigned to the unlicensed band. In scenario 2, half of the voice traffic goes on the licensed band and other half will go through the unlicensed band along with the multimedia traffic. The proposed scenarios are also compared with the existing algorithm, Static mapping scheme (SMS), to evaluate the performance.

Static Mapping Scheme (SMS): In SMS cellular users are first ordered in descending order in terms of SINR of the unlicensed band. The LWA BS sequentially assigns the unlicensed bandwidth and the QoS exponent to the ordered users by solving the following equations [12];

$$e^{-\theta_{b,k} C_{b,k} D_{th}^k} = P_{th}^k \tag{40}$$

$$C_{b,k}(\alpha_{b,k}, \theta_{b,k}) = \frac{z}{\theta_{b,k}} + \alpha_{b,k} log(1 + \overline{\eta}_{b,k}) \tag{41}$$

LWA BS will keep on assigning the unlicensed bandwidth until the total allocated bandwidth reaches the total unlicensed bandwidth or all the QoS users are satisfied. If the unlicensed band is insufficient to satisfy the QoS of the users, the rest of the traffic goes to the licensed band. The remaining users are ordered in descending SINR of the licensed band. The LWA BS sequentially allocate the licensed bandwidth and the QoS exponent to the ordered users by solving the following equations,

$$e^{-\theta_{a,k} C_{a,k} D_{th}^k} = P_{th}^k \tag{42}$$

$$C_{a,k}(\alpha_{a,k}, \theta_{a,k}) = -\frac{1}{\theta_{a,k} T} \log(\mathbb{E}_\gamma\{e^{-\theta_{a,k}\alpha_{a,k} T \log_2(1+\gamma)}\}) \tag{43}$$

A static mapping table is established where a design parameter η ($0 \leq \eta \leq 1$) is decided according to the QoS Class Indicator (QCI) or the types of traffics. In the simulations, we assigned η = 0.7.

In Fig. 4, we investigate the bandwidth of licensed band with the delay requirements, where P_V=0.3, P_M=0.7, P_D=0.6 and P_{ND}=0.4. There are in total 10 users within the coverage area of LTE and Wi-Fi. The figure shows that as the delay bound increases the required bandwidth of the licensed band decreases. It can also be observed that the our proposed

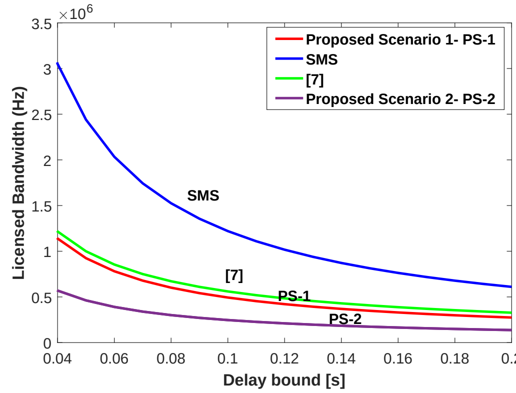

Fig. 4: Licensed Bandwidth vs Delay Bound: P_V=0.3, P_M=0.7, P_{ND}=0.4, and P_D=0.6

scenarios performs better in terms of delay as compared to the existing scheme in [12] and SMS scheme. Also, proposed scenario 2 can perform much better than scenario 1, when the voice traffic is split between the licensed and unlicensed band.

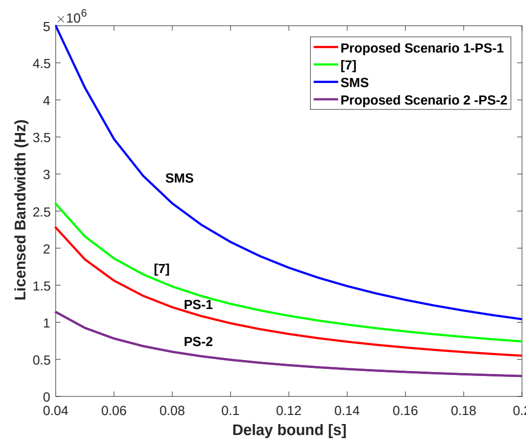

Fig. 5: Licensed Bandwidth vs Delay Bound: P_V=0.6, P_M=0.4, P_{ND}=0.4, and P_D=0.4

In Fig. 5, the values of probabilities are changed to further observe the behaviour of licensed bandwidth with the delay requirements. The Fig. 5 is plotted for P_V=0.4, P_M=0.6, P_D=0.4 and P_{ND}=0.4. It can be observed that by increasing the probability of voice users will increase the requirement of licensed bandwidth as well. Also, our proposed scheme performs better than the existing scheme in [12] and the SMS scheme.

In Fig. 6 and 7, the required licensed bandwidth is investigated with the number of transmitters by changing the value of probabilities. The required licensed bandwidth increases with the increase of transmitters. In Fig. 7, the voice probability is increased and the requirement for licensed bandwidth also increases. Also, it can be observed that our proposed scheme can reduce the licensed bandwidth as compared to the existing scheme in [12] and SMS. Scenario 2 can provide 50% less

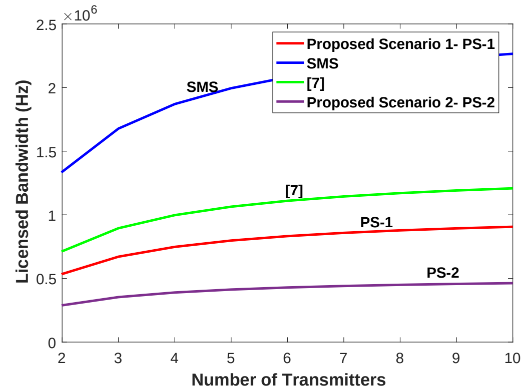

Fig. 6: Licensed Bandwidth vs Number of Transmitters: P_V=0.3, P_M=0.7, P_{ND}=0.4, and P_D=0.6

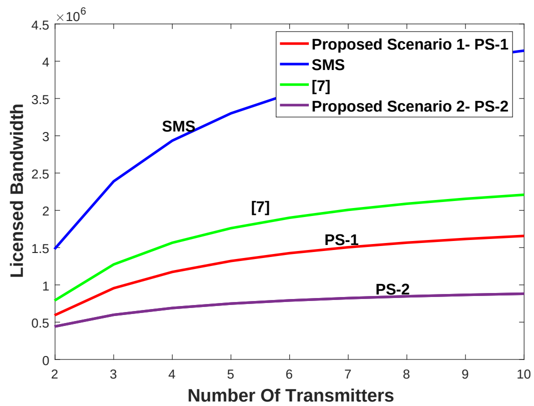

Fig. 7: Licensed Bandwidth vs Number of Transmitters: P_V=0.6, P_M=0.4, P_{ND}=0.4, and P_D=0.4

requirement of licensed band as than scenario 1.

In Fig. 8 and 9, we investigate the delay bound with the number of transmitters by changing the probabilities. All users have the same delay threshold D^n_{th} = 0.05 s. The delay increases as the transmitter increases but our proposed schemes can reduce the delay as compared to the existing scheme in [12] and the SMS scheme. Scenario 2 can further reduce the delay as compared with scenario 1.

VII. Conclusion

In the proposed paper, we investigate an optimal queue scheduling and resource allocation problem under various statistical delay constraints of three-tier network. The three-tier network is based on LWA technology with modification in resource allocation scheme based on IEEE 802.11 PCF to access WLAN channels. Multimedia files are further offloaded using D2D communication. A closed-form expression of effective capacity for the unlicensed band is derived using semi-Markovian process. Secondly, we formulate the optimal joint queue scheduling and resource allocation problem with the QoS guarantee between licensed and unlicensed band to minimize the bandwidth of licensed band. An iterative

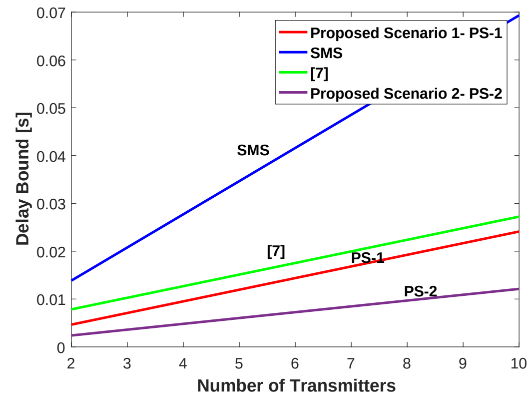

Fig. 8: Delay Bound vs Number of Transmitters: P_V=0.3, P_M=0.7, P_{ND}=0.4, and P_D=0.6

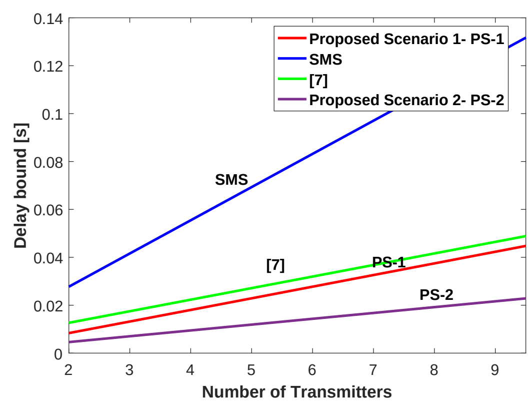

Fig. 9: Delay Bound vs Number of Transmitters: P_V=0.6, P_M=0.4, P_{ND}=0.4, and P_D=0.4

algorithm is proposed to convexify the problem as a series of block coordinated descent (BCD) and difference of convex functions (D.C) program. Further, the simulation was carried out with our proposed scheme with two scenarios, in the first scenario all the voice traffic uses the licensed band and multimedia traffic uses the unlicensed band, and the second scenario split the voice traffic to licensed and unlicensed band whereas all the multimedia traffic goes to unlicensed band. The simulation results showed that our proposed scheme can provide improved performance than the existing scheme in [12] and SMS scheme. Also scenario 2 can perform 50% better than scenario 1.

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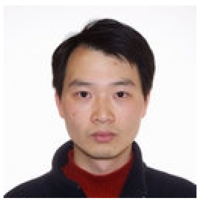
Bushra Ismaiel -is currently working towards her PhD degree with the School of Electrical and Data Engineering, University Of Technology Sydney, Australia. She completed her B.E from University Of Texas at Dallas, USA and M.E from University of South Carolina, USA. Her current research interests are in D2D communication, IoT, Wireless, Applications of IoT and 5G. She has worked in Wireless industry for 5-6 years as a Team Lead, RF Engineer and Junior Project Manager

A/Prof Mehran Abolhasan -completed his B.E in Computer Engineering and PhD in Telecommunications on 1999 and 2003 respectively at the University of Wollongong. He is currently an Associate Professor and Deputy Head of School at School of Electrical and Data Engineering at UTS. A/Prof. Abolhasan has authored over 120 international publications and has won over 3 million dollars in research funding. His Current research Interests are in Software Defined Networking, IoT, Wireless Mesh, Wireless Body Area Networks, Cooperative Networks, 5G Networks and Beyond and Sensor networks. He is currently a Senior Member of IEEE.



Wei Ni -received the B.E. and Ph.D. degrees in Electronic Engineering from Fudan University, Shanghai, China, in 2000 and 2005, respectively. Currently he is a Team Leader, Senior Scientist, and Project Leader at CSIRO, Sydney, Australia. He also holds honorary positions at the University of New South Wales (UNSW), Macquarie University (MQ) and the University of Technology Sydney (UTS). His research interests include optimization, game theory, graph theory, as well as their applications to network and security. Dr Ni serves as Vice Chair of IEEE NSW VTS Chapter since 2018, served as Editor for Hindawi Journal of Engineering from 2012 – 2015, secretary of IEEE NSW VTS Chapter from 2015-2018, Track Chair for VTC-Spring 2017, Track Co-chair for IEEE VTC-Spring 2016, and Publication Chair for BodyNet 2015. He also served as Student Travel Grant Chair for WPMC 2014, a Program Committee Member of CHINACOM 2014, a TPC member of IEEE ICC14, ICCC15, EICE14, and WCNC10.

David Smith -(S'01-M'04) received the B.E. degree in electrical engineering from the University of New South Wales, Sydney, NSW, Australia, in 1997, and the M.E. (research) and Ph.D. degrees in telecommunications engineering from the University of Technology, Sydney, NSW, Australia, in 2001 and 2004, respectively. Since 2004, he was with National Information and Communications Technology Australia (NICTA, incorporated into Data61 of CSIRO in 2016), and the Australian National University (ANU), Canberra, ACT, Australia, where he is currently a Senior Research Scientist with Data61 CSIRO, and an Adjunct Fellow with ANU. His current research interests include wireless body area networks, game theory for distributed networks, disaster tolerant networks, 5G networks, IoT, antenna design, distributed optimization for smart grid and privacy for networks. He has published over 100 technical refereed papers. Dr. Smith was the recipient of four conference Best Paper Awards.

Daniel Franklin - completed his PhD in Telecommunications Engineering, "Enhancements to Channel Models, DMT Modulation and Coding for Channels Subject to Impulsive Noise", at the University of Wollongong (2007) and also holds a Bachelor of Engineering (electrical) - Honours I, University of Wollongong (1999). He has been a member of the IEEE since 1998. He is currently a Senior Lecturer in the Faculty of Engineering and Information Technology at the University of Technology Sydney. His current research and commercial interests include multimedia and signal processing, wireless communication systems, positron emission tomography, radiotherapy, radiation dosimetry and pharmacokinetic modelling.

Eryk Dutkiewicz - received his B.E. degree in Electrical and Electronic Engineering from the University of Adelaide in 1988, his M.Sc. degree in Applied Mathematics from the University of Adelaide in 1992 and his PhD in Telecommunications from the University of Wollongong in 1996. His industry experience includes management of the Wireless Research Laboratory at Motorola in early 2000. He is currently the Head of School of Electrical and Data Engineering at the University of Technology Sydney, Australia. He also holds a professorial appointment at Hokkaido University in Japan. His current research interests cover 5G and IoT networks.

Marwan M. Krunz - is the Kenneth VonBehren Endowed Professor in the ECE Department at the University of Arizona. He is also an affiliated faculty member of the University of Technology Sydney (UTS). He directs the Broadband Wireless Access and Applications Center, a multi-university industry-focused NSF center that includes affiliates from industry and government labs. He previously served as the UA site director for Connection One, an NSF IUCRC that focuses on wireless communication circuits and systems. In 2010, Dr. Krunz was a Visiting Chair of Excellence at the University of Carlos III de Madrid. He previously held visiting research positions at UTS, INRIA-Sophia Antipolis, HP Labs, University of Paris VI, University of Paris V, University of Jordan, and US West Advanced Technologies. Dr. Krunzs research interests lie in the areas of wireless communications and networking, with emphasis on resource management, adaptive protocols, and security issues. He has published more than 270 journal articles and peer-reviewed conference papers, and is a co-inventor on several US patents. He is an IEEE Fellow, an Arizona Engineering Faculty Fellow (2011-2014), and an IEEE Communications Society Distinguished Lecturer (2013 and 2014). He was the recipient of the 2012 IEEE TCCC Outstanding Service Award. He received the NSF CAREER award in 1998. He currently serves as the Editor-in-Chief for the IEEE Transactions on Mobile Computing. He previously served on the editorial boards for the IEEE Transactions on Cognitive Communications and Networks, IEEE/ACM Transactions on Networking, IEEE TMC, IEEE Transactions on Network and Service Management, Computer Communications Journal, and IEEE Communications Interactive Magazine. See http://www2.engr.arizona.edu/ krunz/ for more details.

Abbas Jamalipour -(S'86-M'91-SM'00-F'07) is the Professor of Ubiquitous Mobile Networking at the University of Sydney, Australia, and holds a PhD in Electrical Engineering from Nagoya University, Japan. He is a Fellow of the Institute of Electrical, Information, and Communication Engineers (IEICE) and the Institution of Engineers Australia, an ACM Professional Member, and an IEEE Distinguished Lecturer. He has authored six technical books, eleven book chapters, over 450 technical papers, and five patents, all in the area of wireless communications. He was the Editor-in-Chief IEEE Wireless Communications (2006-08), Vice President-Conferences (2012-13) and a member of Board of Governors of the IEEE Communications Society, and has been an editor for several journals. He was a General Chair or Technical Program Chair for a number of conferences, including IEEE ICC, GLOBECOM, WCNC and PIMRC. Dr. Jamalipour is an elected member of the Board of Governors (2014-16 and 2017-19), Executive Vice-President, Chair of Fellow Evaluation Committee, and the Editor-in-Chief of the Mobile World, IEEE Vehicular Technology Society. He is the recipient of a number of prestigious awards such as the 2016 IEEE ComSoc Distinguished Technical Achievement Award in Communications Switching and Routing, 2010 IEEE ComSoc Harold Sobol Award, and the 2006 IEEE ComSoc Best Tutorial Paper Award.