

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 M. 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 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, 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, 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 nonconvex problem as a series of subproblems based on block coordinate descent 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 the 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 a days 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 aspect in D2D communication, and most of the work has been done using cellular network [8].

Manuscript received July 18, 2018; accepted September 22, 2018. Date of publication October 4, 2018; date of current version December 14, 2018. The review of this paper was coordinated by Dr. D. Marabissi. (Corresponding author: Bushra Ismaiel.)

B. Ismaiel, M. Abolhasan, D. Franklin, and E. Dutkiewicz are 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 with Data61, Commonwealth Scientific and Industrial Research Organisation, Clayton, VIC 3169, Australia (e-mail: Wei.Ni@data61.csiro.au; david.smith@data61.csiro.au).

M. M. Krunz is with the Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ 85721 USA (e-mail: krunz@email.arizona.edu).

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

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TVT.2018.2873732

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, sub-band 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

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

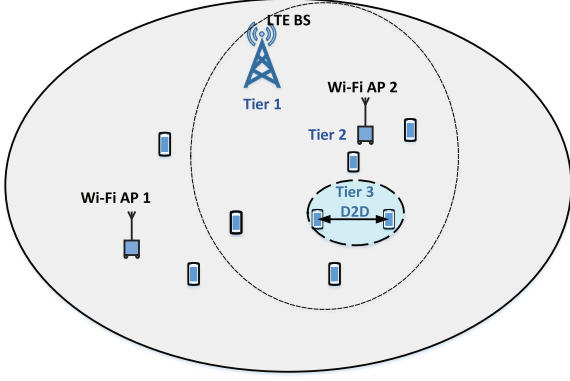


Fig. 1. Proposed three-tier heterogeneous network.

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 overlaid 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 $k = 1, \dots, K$. 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_{th}^k and the maximum probability threshold of the delay bound being violated is P_{th}^k . 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];

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

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

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

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

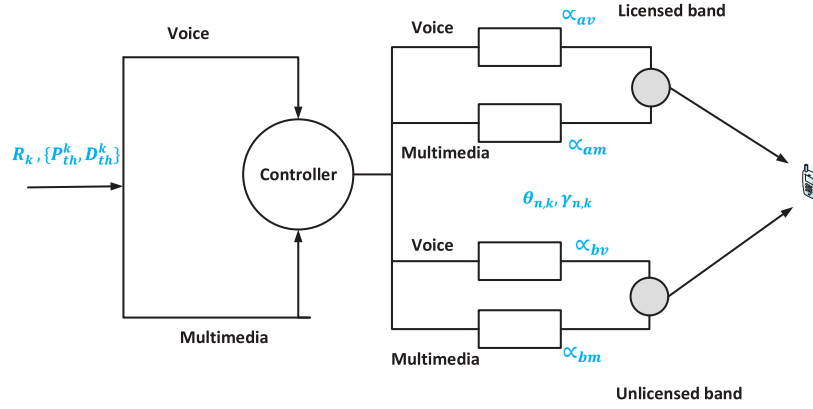


Fig. 2. Queuing model of three-tier network.

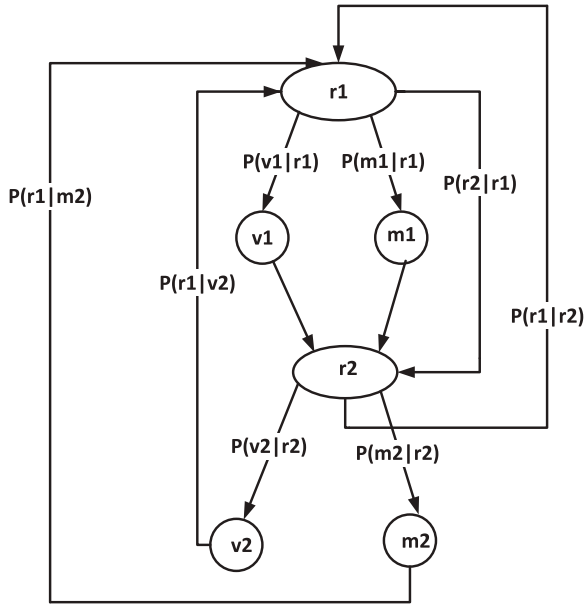


Fig. 3. SC-MP semi-Markovian model.

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.

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

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 $k = 1, \dots, K$.

The transition probability from polling state r_1 to v_1 for user₁ is given as

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

Similarly, the transition probability for user₂ is given as

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

where P_{V1} and P_{V2} are the probabilities of voice traffic for user₁ and user₂. $1-P_{S1}$ and $1-P_{S2}$ are the probabilities that satisfies the channel condition E for time slot allocation for user₁ and user₂ for voice and video/multimedia traffic.

The transition probability from r_1 to m_1 is given as

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

Similarly, for user₂ the transition probability is given as

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

where P_{M1} and P_{M2} are the probabilities of video/multimedia traffic for user₁ and user₂. $1 - P_{S1}$ and $1 - P_{S2}$ are the probabilities that satisfies the channel condition E for time slot allocation for user₁ and user₂, N_n is the total number of neighbours that downloaded the video, P_{ND1} and P_{ND2} are the probabilities that video requested by user₁ and user₂ 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 user₁ and user₂. The transition probability for polling state r_1 to polling state r_2 is given as

$$P_{E1} = 1 - P_{A1} - P_{F1} \quad (9)$$

$$P_{E2} = 1 - P_{A2} - P_{F2} \quad (10)$$

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

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

The duration of both states r_1 and r_2 is T_{r1} and T_{r2} and is constant for both users. The duration for v_1 and v_2 is random and denoted by T_{v1} and T_{v2} , 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 downloading traffic.

The moment generating functions (MGF) of T_{r1} , T_{v1} , T_{m1} , T_{r2} , T_{v2} , and T_{m2} are $M_1(t) = e^{tT_{r1}}$, $M_2(t) = \Sigma e^{tT_{v1}}P_{A1}$, $M_3(t)$

$$= \Sigma e^{tT_{m1}}P_{F1}, M_4(t) = e^{tT_{r2}}, M_5(t) = \Sigma e^{tT_{v2}}P_{A2}, \text{ and } M_6(t) = \Sigma e^{tT_{m2}}P_{F2}.$$

We define two auxiliary variables, s and u , with reference to [24], [35]. We now create a diagonal matrix $\Gamma(s, u)$. The diagonal elements of $\Gamma(s, u)$ are the MGFs of the six state semi-Markovian model and is given in (12), shown at the bottom of the page. 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 $\phi(s, u) = \rho(\mathbf{H}(s, u))$ is a simple eigenvalue of $\mathbf{H}(s, u)$ and $\rho(\cdot)$ represents the spectra radius.

We can write for each permissible pair of s and u $\mathbf{H}(s, u) = \Gamma(s, u)\mathbf{Q}$ and is given in (13), shown at the bottom of the page.

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

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 $(\mathbf{H}(-\theta, -\theta C))$, we have (14), shown at the bottom of the next page, where $\mathbf{I}$ is the identity matrix and $|\cdot|$ is the determinant of the matrix. The determinant is given in (15), shown at the bottom of the next page, where

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

We substitute the $\lambda = \phi(-\theta, -\theta C) = 1$ 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;

$$C_{bv}(\alpha_{bv}, \theta_b) = \frac{z}{\theta_b} + \alpha_{bv} \log(1 + \bar{\gamma}_b) \quad (16)$$

$$C_{bm}(\alpha_{bm}, \theta_b) = \frac{z}{\theta_b} + \alpha_{bm} \log(1 + \bar{\gamma}_b) \quad (17)$$

where $\bar{\gamma}_b$ is signal-to-interference-noise ratio (SINR) of a user in unlicensed band and z is a constant value and varies with the

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

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

value of probabilities defined, that is; P_V, P_M, P_D and P_{ND} for every user. We can 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];

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

where $\bar{\gamma}_{a,k}$ 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:

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

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

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

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

$$\text{s.t.}, \frac{\sum_{n \in N} y_{n,k} e^{-\theta_{n,k} C_{n,k}(\theta_{n,k}) D_{th}^k} C_{n,k}(\theta_{n,k})}{\sum_{n \in N} y_{n,k} C_{n,k}(\theta_{n,k})} \leq P_{th}^k, \forall k \in K \quad (21b)$$

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

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

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

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

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 $\mathbf{P1}$, $e^{-\theta_{n,k} C_{n,k} D_{th}^k}$ 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

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

By using the inequality [38];

$$0 \leq \alpha_{n,k} \leq y_{n,k} \chi \quad (23)$$

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

$$\sum_{n \in N} e^{-\theta_{n,k} C_{n,k}(\theta_{n,k}) D_{th}^k} C_{n,k} \leq P_{th}^k \sum_{n \in N} C_{n,k} \quad (24)$$

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

$$\frac{1}{|N|} \sum_{n \in N} e^{-\theta_{n,k} C_{n,k}(\theta_{n,k}) D_{th}^k} \sum_{n \in N} C_{n,k} \leq P_{th}^k \sum_{n \in N} C_{n,k} \quad (25)$$

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

$$e^{-\theta_{n,k} C_{n,k}(\theta_{n,k}) D_{th}^k} \leq P_{th}^k \quad (26)$$

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

$$\sum_{n \in N} e^{-\theta_{n,k} C_{n,k}(\theta_{n,k}) D_{th}^k} - 1 + y_{n,k} \leq P_{th}^k \sum_{n \in N} y_{n,k} \quad (27)$$

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

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

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

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

$$0 \leq y_{n,k} \leq 1, \forall k \in K, \forall n \in N \quad (28)$$

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

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

$$C_{av,k}(\omega_{av,k}, \beta_{a,k}) = -\frac{\beta_{a,k}}{T} \log \left(\mathbb{E}_\gamma \left\{ e^{-\omega_{av,k} T \log_2(1+\gamma_a)} \right\} \right) \quad (30)$$

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

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

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

$$\begin{aligned} & e^{\frac{\log(\mathbb{E}_\gamma \{ e^{-\omega_{av,k} T \log_2(1+\gamma_a)} \})}{T} D_{th}^k} \\ & + e^{-(2z + \omega_{bv} \beta_b \log_2(1+\gamma_b) + \omega_{bm} \beta_b \log_2(1+\gamma_b)) D_{th}^k} - 2 \\ & + \sum_{n \in N} y_{n,k} \leq P_{th}^k \sum_{n \in N} y_{n,k}, \forall k \in K \end{aligned} \quad (33)$$

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

$$\mathbf{P2} : \underset{\{\omega_{n,k}\}, \{\beta_{n,k}\}, \{y_{n,k}\}}{\text{minimize}} \sum_{k \in K} \omega_{a,k} \beta_{a,k} \quad (34a)$$

$$\begin{aligned} & e^{\frac{\log(\mathbb{E}_\gamma \{ e^{-\omega_{av,k} T \log_2(1+\gamma_a)} \})}{T} D_{th}^k} \\ & + e^{-(2z + \omega_{bv} \beta_b \log_2(1+\gamma_b) + \omega_{bm} \beta_b \log_2(1+\gamma_b)) D_{th}^k} - 2 \\ & + \sum_{n \in N} y_{n,k} \leq P_{th}^k \sum_{n \in N} y_{n,k}, \forall k \in K \end{aligned} \quad (34b)$$

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

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

$$\sum_{n \in N} y_{n,k} \geq 1, \forall k \in K \quad (34e)$$

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

$$\omega_{n,k} \geq 0, \beta_{n,k} \geq 0, 0 \leq y_{n,k} \leq 1, \forall n \in N, \forall k \in K \quad (34g)$$

$$0 \leq \omega_{a,n} \beta_{a,n} \leq y_{n,k} \chi, \forall k \in K, \forall n \in N \quad (34h)$$

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**

$$\begin{aligned} \mathbf{P3} : \underset{\{\omega_{n,k}\}, \{y_{n,k}\}}{\text{minimize}} & \sum_{k \in K} \omega_{a,k} \beta_{a,k} + \lambda \sum_{n \in N} \sum_{k \in K} y_{n,k} \\ & - \lambda \sum_{n \in N} \sum_{k \in K} (y_{n,k})^2, \end{aligned} \quad (35)$$

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

where λ is a large penalty factor.

Let;

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

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

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

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

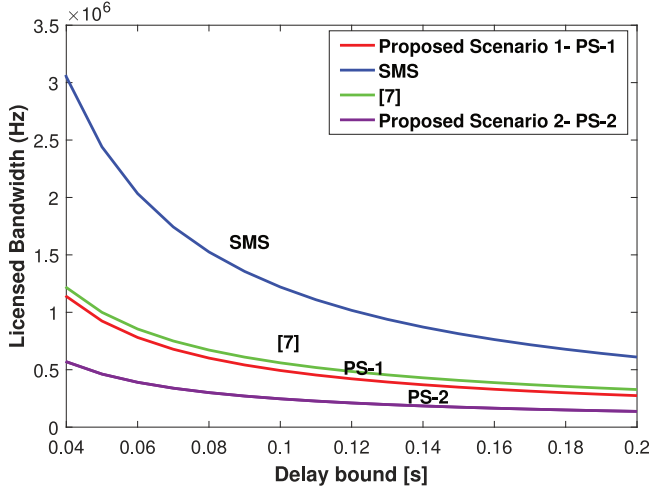


Fig. 4. Licensed bandwidth vs delay bound: $P_V = 0.3$, $P_M = 0.7$, $P_{ND} = 0.4$, and $P_D = 0.6$.

the following equations [12];

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

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

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,

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

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

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 $\eta = 0.7$.

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 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.

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 li-

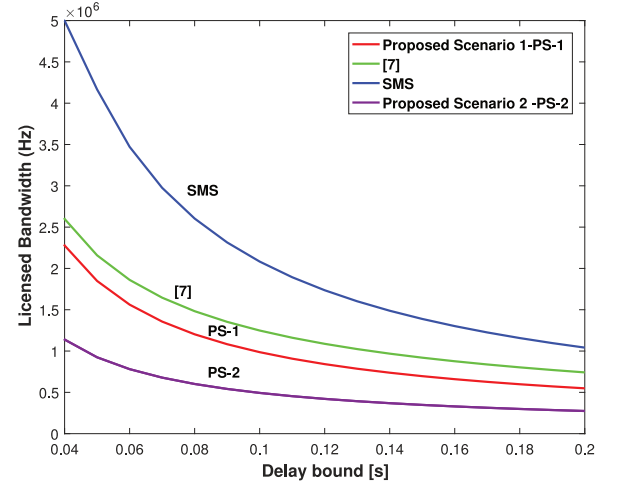


Fig. 5. Licensed bandwidth vs delay bound: $P_V = 0.6$, $P_M = 0.4$, $P_{ND} = 0.4$, and $P_D = 0.4$.

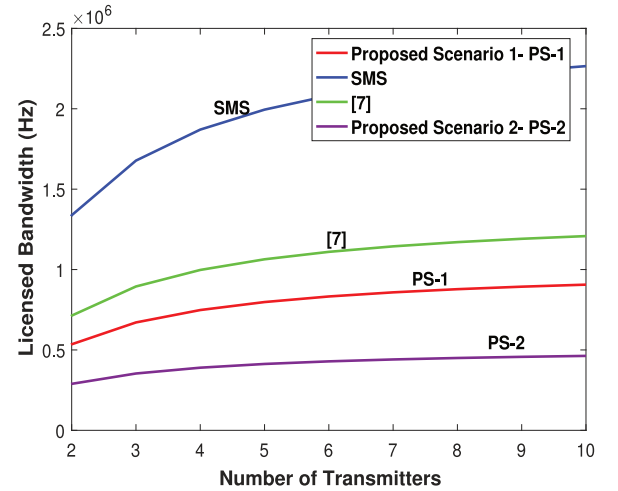


Fig. 6. Licensed bandwidth vs number of transmitters: $P_V = 0.3$, $P_M = 0.7$, $P_{ND} = 0.4$, and $P_D = 0.6$.

censed bandwidth as well. Also, our proposed scheme performs better than the existing scheme in [12] and the SMS scheme.

In Figs. 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 requirement of licensed band as than scenario 1.

In Figs. 8 and 9, we investigate the delay bound with the number of transmitters by changing the probabilities. All users have the same delay threshold $D_{th}^n = 0.05$ 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.

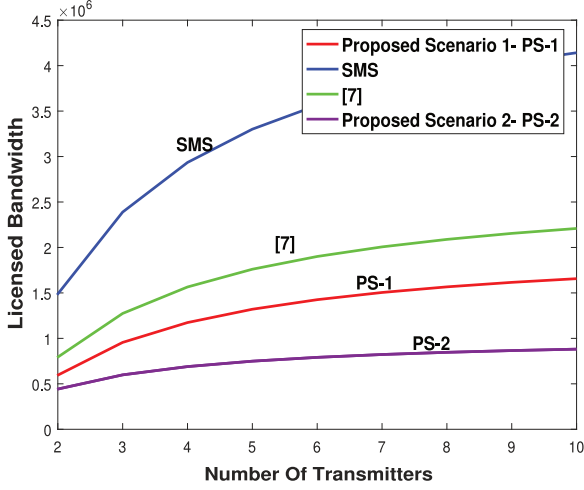


Fig. 7. Licensed bandwidth vs number of transmitters: $P_V = 0.6$, $P_M = 0.4$, $P_{ND} = 0.4$, and $P_D = 0.4$.

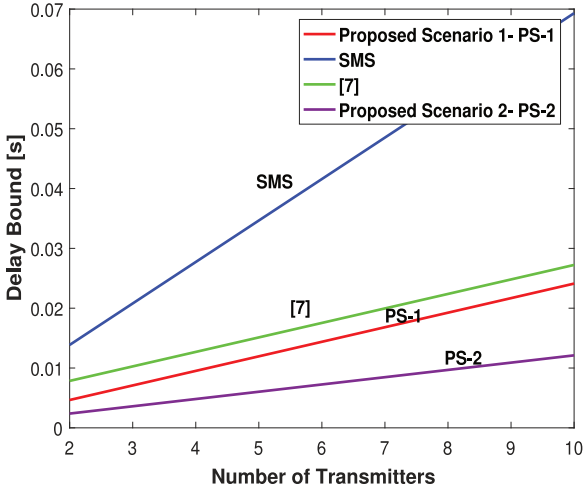


Fig. 8. Delay bound vs number of transmitters: $P_V = 0.3$, $P_M = 0.7$, $P_{ND} = 0.4$, and $P_D = 0.6$.

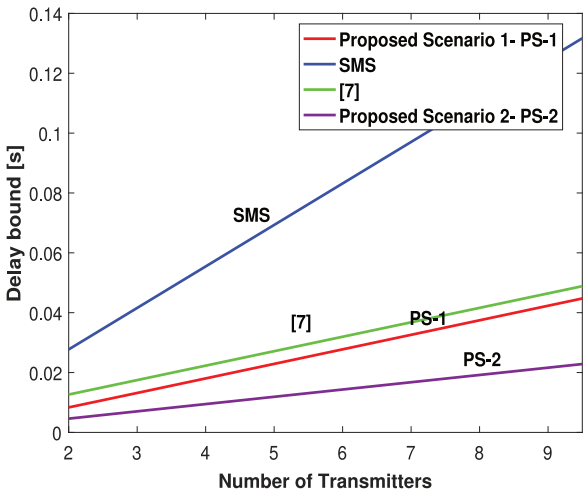


Fig. 9. Delay bound vs number of transmitters: $P_V = 0.6$, $P_M = 0.4$, $P_{ND} = 0.4$, and $P_D = 0.4$.

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 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.

REFERENCES

- [1] K. Doppler, M. Rinne, C. Wijting, C. B. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *IEEE Commun. Mag.*, vol. 47, no. 12, pp. 42–49, Dec. 2009.
- [2] 3GPP, "Collaboration on LTE-WLAN Integration," 2016. [Online]. Available: http://www.3gpp.org/news-events/3gpp-news/1771-WLAN_LTE
- [3] L. Li, J. P. Seymour, L. J. Cimini, and C.-C. Shen, "Coexistence of Wi-Fi and LAA networks with adaptive energy detection," *IEEE Trans. Veh. Technol.*, vol. 66, no. 11, pp. 10384–10393, Nov. 2017.
- [4] Q. Cui *et al.*, "Preserving reliability of heterogeneous ultra-dense distributed networks in unlicensed spectrum," *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 72–78, Jun. 2018.
- [5] S. Andreev, A. Pyattaev, K. Johnsson, O. Galinina, and Y. Koucheryavy, "Cellular traffic offloading onto network-assisted device-to-device connections," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 20–31, Apr. 2014.
- [6] J. Liu, N. Kato, J. Ma, and N. Kadowaki, "Device-to-device communication in LTE-advanced networks: A survey," *IEEE Commun. Surv. Tuts.*, vol. 17, no. 4, pp. 1923–1940, Oct.–Dec. 2015.
- [7] J. Liu, N. Kato, H. Ujikawa, and K. Suzuki, "Device-to-device communication for mobile multimedia in emerging 5G networks," *ACM Trans. Multimedia Comput., Commun. Appl.*, vol. 12, no. 5s, 2016, Art. no. 75.
- [8] J. Dai, J. Liu, Y. Shi, S. Zhang, and J. Ma, "Analytical modeling of resource allocation in D2D overlaying multihop multichannel uplink cellular networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 6633–6644, Aug. 2017.
- [9] N. Golrezaei, P. Mansourifard, A. F. Molisch, and A. G. Dimakis, "Base-station assisted device-to-device communications for high-throughput wireless video networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 7, pp. 3665–3676, Jul. 2014.
- [10] A. Antonopoulos, E. Kartsakli, and C. Verikoukis, "Game theoretic D2D content dissemination in 4G cellular networks," *IEEE Commun. Mag.*, vol. 52, no. 6, pp. 125–132, Jun. 2014.
- [11] E. Datsika, A. Antonopoulos, N. Zorba, and C. Verikoukis, "Cross-network performance analysis of network coding aided cooperative out-band D2D communications," *IEEE Trans. Wireless Commun.*, vol. 16, no. 5, pp. 3176–3188, May 2017.
- [12] Y. Gu, Q. Cui, W. Ni, P. Zhang, and W. Zhuang, "Optimal scheduling across heterogeneous air interfaces of LTE/WiFi aggregation," *IEEE Int. Conf. Commun. (ICC)*, 2018.
- [13] B. P. Crow, I. Widjaja, J. G. Kim, and P. Sakai, "Investigation of the IEEE 802.11 medium access control (MAC) sublayer functions," in *Proc. 16th Annu. Joint Conf. IEEE Comput. Commun. Soc. Driving Inf. Revolution*, 1997, vol. 1, pp. 126–133.

- [14] M. A. Visser and M. El Zarki, "Voice and data transmission over an 802.11 wireless network," in *Proc. 16th IEEE Int. Symp. Pers., Indoor Mobile Radio Commun.*, 1995, vol. 2, pp. 648–652.
- [15] J. Wu and G. Huang, "Simulation study based on QoS schemes for IEEE 802.11," in *Proc. 3rd Int. Conf. Adv. Comput. Theory Eng.*, 2010, vol. 6, pp. V6-534–V6-538.
- [16] S. Sharma, K. Kim, C. Oh, and A. Ahmad, "Performance evaluation of IEEE 802.11 MAC protocol for multimedia services," in *Proc. Asia-Pacific Conf. Commun./Int. Conf. Conceptual Struct.*, 1998, pp. 181–185.
- [17] T. Suzuki and S. Tasaka, "Performance evaluation of integrated video and data transmission with the IEEE 802.11 standard MAC protocol," in *Proc. IEEE Global Telecommun. Conf.*, 1999, vol. 1, pp. 580–586.
- [18] A. Antonopoulos, C. Verikoukis, C. Skianis, and O. B. Akan, "Energy efficient network coding-based MAC for cooperative ARQ wireless networks," *Ad Hoc Netw.*, vol. 11, no. 1, pp. 190–200, 2013.
- [19] J. Li, Y. Ding, Q. Ye, N. Zhang, and W. Zhuang, "On effective capacity and effective energy efficiency in relay-assisted wireless networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 4389–4400, May 2018.
- [20] O. Galinina, A. Pyattaev, S. Andreev, M. Dohler, and Y. Koucheryavy, "5G multi-RAT LTE-WiFi ultra-dense small cells: Performance dynamics, architecture, and trends," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 6, pp. 1224–1240, Jun. 2015.
- [21] F. Liu, E. Bala, E. Erkip, M. C. Beluri, and R. Yang, "Small-cell traffic balancing over licensed and unlicensed bands," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5850–5865, Dec. 2015.
- [22] A. R. Elsharif, W.-P. Chen, A. Ito, and Z. Ding, "Resource allocation and inter-cell interference management for dual-access small cells," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 6, pp. 1082–1096, Jun. 2015.
- [23] M. Bennis, M. Simsek, A. Czylik, W. Saad, S. Valentin, and M. Debbah, "When cellular meets WiFi in wireless small cell networks," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 44–50, Jun. 2013.
- [24] E. Kafetzakis, K. Kontovasilis, and I. Stavrakakis, "A novel effective capacity-based framework for providing statistical QoS guarantees in IEEE 802.11 WLANs," *Comput. Commun.*, vol. 35, no. 2, pp. 249–262, 2012.
- [25] Q. Cui *et al.*, "A unified protocol stack solution for LTE and WLAN in future mobile converged networks," *IEEE Wireless Commun.*, vol. 21, no. 6, pp. 24–33, Dec. 2014.
- [26] A. A. Khalek, C. Caramanis, and R. W. Heath, "Delay-constrained video transmission: Quality-driven resource allocation and scheduling," *IEEE J. Sel. Topics Signal Process.*, vol. 9, no. 1, pp. 60–75, Feb. 2015.
- [27] D. Wu and R. Negi, "Effective capacity: A wireless link model for support of quality of service," *IEEE Trans. Wireless Commun.*, vol. 2, no. 4, pp. 630–643, Jul. 2003.
- [28] X. Zhang, J. Tang, H.-H. Chen, S. Ci, and M. Guizani, "Cross-layer-based modeling for quality of service guarantees in mobile wireless networks," *IEEE Commun. Mag.*, vol. 44, no. 1, pp. 100–106, Jan. 2006.
- [29] M. Abolhasan, J. Lipman, W. Ni, and B. Hagelstein, "Software-defined wireless networking: Centralized, distributed, or hybrid?" *IEEE Netw.*, vol. 29, no. 4, pp. 32–38, Jul./Aug. 2015.
- [30] R. Masoudi and A. Ghaffari, "Software defined networks: A survey," *J. Netw. Comput. Appl.*, vol. 67, pp. 1–25, 2016.
- [31] B. Ismaiel, M. Abolhasan, D. Smith, W. Ni, and D. Franklin, "Scalable MAC protocol for D2D communication for future 5G networks," in *Proc. 14th IEEE Annu. Consum. Commun. Netw. Conf.*, 2017, pp. 542–547.
- [32] A. Köpsel, J.-P. Ebert, and A. Wolisz, "A performance comparison of point and distributed coordination function of an IEEE 802.11 WLAN in the presence of real-time requirements," in *Proc. 7th Int. Workshop Mobile Multimedia Commun.*, 2000.
- [33] L. Musavian and Q. Ni, "Effective capacity maximization with statistical delay and effective energy efficiency requirements," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3824–3835, Jul. 2015.
- [34] A. H. Anwar, K. G. Seddik, T. ElBatt, and A. H. Zahran, "Effective capacity of delay-constrained cognitive radio links exploiting primary feedback," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 7334–7348, Sep. 2016.
- [35] K. Kontovasilis and N. Mitrou, "Effective bandwidths for a class of non Markovian fluid sources," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 27, no. 4, pp. 263–274, 1997.
- [36] Q. Cui, Y. Gu, W. Ni, and R. P. Liu, "Effective capacity of licensed-assisted access in unlicensed spectrum: From theory to applications," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 8, pp. 1754–1767, Aug. 2017.
- [37] F. Jin, R. Zhang, and L. Hanzo, "Resource allocation under delay-guarantee constraints for heterogeneous visible-light and RF femtocell," *IEEE Trans. Wireless Commun.*, vol. 14, no. 2, pp. 1020–1034, Feb. 2015.
- [38] E. Che, H. D. Tuan, and H. H. Nguyen, "Joint optimization of cooperative beamforming and relay assignment in multi-user wireless relay networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 10, pp. 5481–5495, Oct. 2014.
- [39] G. H. Hardy, J. E. Littlewood, G. Pólya, *Inequalities*. Oxford, U.K.: Univ. Press, 1952.
- [40] B. Khamidehi, A. Rahmati, and M. Sabbaghian, "Joint sub-channel assignment and power allocation in heterogeneous networks: An efficient optimization method," *IEEE Commun. Lett.*, vol. 20, no. 12, pp. 2490–2493, Dec. 2016.
- [41] N. Tekbiyik, T. Girici, E. Uysal-Biyikoglu, and K. Leblebicioglu, "Proportional fair resource allocation on an energy harvesting downlink," *IEEE Trans. Wireless Commun.*, vol. 12, no. 4, pp. 1699–1711, Apr. 2013.
- [42] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.



Bushra Ismaiel received the B.E. degree from the University of Texas at Dallas, Richardson, TX, USA, and the M.E. degree from the University of South Carolina, Columbia, SC, USA. She is currently working toward the Ph.D. degree with the School of Electrical and Data Engineering, University of Technology Sydney, Ultimo, NSW, Australia. She was with wireless industry for 5–6 years as a Team Lead, an RF Engineer, and a Junior Project Manager. Her current research interests include D2D communication, IoT, Wireless, Applications of IoT and 5G.



Mehran Abolhasan received the B.E. degree in computer engineering and the Ph.D. degree in telecommunications from the University of Wollongong, Wollongong NSW, Australia, in 1999 and 2003, respectively. He is currently an Associate Professor and the Deputy Head of school with the School of Electrical and Data Engineering, University of Technology Sydney, Ultimo, NSW, Australia. He has authored more than 120 international publications and has won more than 3 million dollars in research funding. His current research interests include software defined networking, IoT, wireless mesh, wireless body area networks, cooperative networks, 5G networks and beyond, and sensor networks.



Wei Ni received the B.E. and Ph.D. degrees in electronic engineering from Fudan University, Shanghai, China, in 2000 and 2005, respectively. He is a Team Leader, a Senior Scientist, and a Project Leader with CSIRO, Sydney, NSW, Australia. He also holds honorary positions with the University of New South Wales, Sydney NSW, Australia, Macquarie University, Sydney, NSW, Australia, and the University of Technology Sydney, Sydney, NSW, Australia. His research interests include optimization, game theory, graph theory, as well as their applications to network and security. Since 2018, he has been the Vice Chair of IEEE NSW VTS Chapter, and was an Editor for the *Hindawi Journal of Engineering* from 2012 to 2015, the Secretary for the IEEE NSW VTS Chapter from 2015 to 2018, the Track Chair for VTC-Spring 2017, the Track Cochair for IEEE VTC-Spring 2016, and the Publication Chair for BodyNet 2015. He also was a Student Travel Grant Chair for WPMC 2014, a Program Committee Member for CHINACOM 2014, and a TPC member for the IEEE ICC14, ICC15, EICE14, and WCNC10.



is currently a Senior Research Scientist with Data61 CSIRO, and an Adjunct Fellow with ANU. He has published more than 100 technical refereed papers. 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 was the recipient of four conference Best Paper Awards.

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 has been with the 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



multimedia and signal processing, wireless communication systems, positron emission tomography, radiotherapy, radiation dosimetry and pharmacokinetic modelling.

Daniel Franklin (M'98) received the Bachelor of Engineering degree (Hons.) in electrical and the Ph.D. degree in telecommunications engineering, "Enhancements to Channel Models, DMT Modulation, and Coding for Channels Subject to Impulsive Noise," from the University of Wollongong, Wollongong, NSW, USA, in 1999 and 2007, respectively. He is currently a Senior Lecturer with the Faculty of Engineering and Information Technology, University of Technology Sydney, Sydney, NSW, Australia.

His current research and commercial interests include



Sydney, NSW, Australia. He also holds a Professorial Appointment with Hokkaido University, Japan. His current research interests include 5G and IoT networks.

Eryk Dutkiewicz received the B.E. degree in electrical and electronic engineering and the M.Sc. degree in applied mathematics from the University of Adelaide, Adelaide, SA, Australia, in 1988, and 1992, respectively, and the Ph.D. degree in telecommunications from the University of Wollongong, Wollongong NSW, Australia, in 1996. His industry experience includes management from the Wireless Research Laboratory, Motorola in early 2000. He is currently the Head of the School of Electrical and Data Engineering, University of Technology Sydney,



One, an NSF IUCRC that focuses on wireless communication circuits and systems. In 2010, he was a Visiting Chair of Excellence with 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. He has authored or coauthored more than 270 journal articles and peer-reviewed conference papers, and is a co-inventor on several US patents. His research interests lie in the areas of wireless communications and networking, with emphasis on resource management, adaptive protocols, and security issues. He is currently an Editor-in-Chief for the IEEE TRANSACTIONS ON MOBILE COMPUTING. He was on the editorial boards for the IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKS, the IEEE/ACM TRANSACTIONS ON NETWORKING, the IEEE TRANSACTIONS ON MOBILE COMPUTING, the IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT, *Computer Communications Journal*, and the IEEE COMMUNICATIONS INTERACTIVE MAGAZINE. From 2013 to 2014, he was the IEEE Communications Society Distinguished Lecturer. He was the recipient of the 2012 IEEE TCCC Outstanding Service Award and the 1998 NSF CAREER Award. He was the General Vice-Chair for WiOpt 2016 and General Co-Chair for WiSec 2012. He was the TPC Chair for Wireless Communications and Networking Conference (2016, Networking Track), INFOCOM (2004), Sensor and Ad Hoc Communications and Networks (2005), World of Wireless, Mobile and Multimedia Networks (2006), and Hot Interconnects 9. He has served and continues to serve on the steering and advisory committees of numerous conferences and on the panels of several funding agencies. He was a Keynote Speaker, an Invited Panelist, and a Tutorial Presenter at numerous international conferences. From 2011 to 2014, he was an Arizona Engineering Faculty Fellow.

Marwan M. Krunz is currently the Kenneth Von-Behren Endowed Professor with the Electrical and Computer Engineering Department, University of Arizona, Tucson, AZ, USA. He is also an affiliated Faculty Member with the University of Technology Sydney (UTS), Ultimo, NSW, Australia. He directs the Broadband Wireless Access and Applications Center, a multi-university industry-focused National Science Foundation (NSF) Center, which includes affiliates from the industry and government labs. He was the UA Site Director for Connection



wireless communications. He was the Editor-in-Chief for the IEEE Wireless Communications (2006–2008), the Vice President-Conferences (2012–2013), and a member of the Board of Governors for 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. He is an elected member for the Board of Governors (2014–2016 and 2017–2019), the Executive Vice-President, the Chair for the Fellow Evaluation Committee, and the Editor-in-Chief for 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.

Abbas Jamalipour (S'86–M'91–SM'00–F'07) received the Ph.D. degree in electrical engineering from Nagoya University, Nagoya, Japan. He currently is a Professor in ubiquitous mobile networking with the University of Sydney, Sydney, NSW, Australia. He is a Fellow for the Institute of Electrical, Information, and Communication Engineers and the Institution of Engineers Australia, an ACM Professional Member, and an IEEE Distinguished Lecturer. He has authored 6 technical books, 11 book chapters, more than 450 technical papers, and 5 patents, all in the area of