The Performance Analysis of Cognitive-based Overlay D2D Communication in 5G Networks

Abdullilah Alotaibi[1†] **and Salman A. AlQahtani**[2††],
abdullilah2007@gmail.com salmanq@ksu.edu.sa
King Saud University, Computer Engineering Dept., Riyadh, Saudi Arabia

Abstract
In the near future, it is expected that there will be billions of connected devices using fifth generation (5G) network services. The recently available base stations (BSs) need to mitigate their loads without changing and at the least monetary cost. The available spectrum resources are limited and need to be exploited in an efficient way to meet the ever-increasing demand for services. Device to Device communication (D2D) technology will likely help satisfy the rapidly increasing capacity and also effectively offload traffic from the BS by distributing the transmission between D2D users from one side and the cellular users and the BS from the other side. In this paper, we propose to apply D2D overlay communication with cognitive radio capability in 5G networks to exploit unused spectrum resources taking into account the dynamic spectrum access. The performance metrics; throughput and delay are formulated and analyzed for CSMA-based medium access control (MAC) protocol that utilizes a common control channel for device users to negotiate the data channel and address the contention between those users. Device users can exploit the cognitive radio to access the data channels concurrently in the common interference area. Estimating the achievable throughput and delay in D2D communication in 5G networks is not exploited in previous studies using cognitive radio with CSMA-based MAC protocol to address the contention. From performance analysis, applying cognitive radio capability in D2D communication and allocating a common control channel for device users effectively improve the total aggregated network throughput by more than 60% compared to the individual D2D throughput without adding harmful interference to cellular network users. This approach can also reduce the delay.

Keywords
5G, Cellular networks, D2D communication, device-to-device, overlay, spectrum

1. Introduction

A huge number of connected devices are expected to use 5G network services more than in previous years, and demand for higher data rates to support next-generation applications is also growing. However, with D2D communication and other technologies, 5G networks are expected to meet this demand [1]. 4G networks will likely be replaced with 5G networks With the technology of advanced access named Beam Division Multiple Access and non and quasi-orthogonal or Filter Bank Multicarrier multiple access [2]. These 5G networks are characterized by three features: low delay, ubiquitous connectivity, and high speed data transfer. Moreover, they will likely provide a connected intelligent transportation system and tracking services and also produce energy-efficient and secure communication at a low cost [3].

The first four generations of networks dependent entirely on the BS and hence called network centric. Conversely, 5G concentrates on D2D technology, which is controlled by the device itself and is called device centric. In general, 5G is a collection of many technologies such as Cognitive Radio Networks, D2D communication, Mm-wave communication, Massive Multiple Input Multiple Output (MIMO), and Visible Light Communication [4].

D2D communication is one of the essential parts of the upcoming 5G system used in cellular networks. Basically, it enables devices to communicate with each other without using the infrastructure of the network or the BS which is required in traditional cellular networks, even though the communicating devices are near to each other. Different wireless technologies with short-range such as Bluetooth, Long Term Evolution LTE Direct and you can also use Wi-Fi Direct to enable such D2D communications.

There are two types of D2D techniques in terms of spectrum usage: in-band and out-band D2D communication [5]. The in-band D2D can be further classified into underlay and overlay D2D communication modes as illustrated in Fig.1 below. In underlay mode, both D2D and cellular users share the same spectrum resources. For the overlay mode, a dedicated part of the available spectrum is utilized for D2D communication and the rest is used for cellular communication. Out-band D2D communication mode uses the unlicensed spectrum band and can be classified as controlled and autonomous. In the former, the D2D radio interface is managed by the cellular network, while in the latter, the cellular network controls only the cellular communication and the users control the D2D communication. To utilize network resources efficiently, we

---

Manuscript received February 5, 2024
Manuscript revised February 20, 2024
https://doi.org/10.22937/IJCSNS.2024.24.2.22

must choose the type of D2D communication mode that best fits the current network situation.

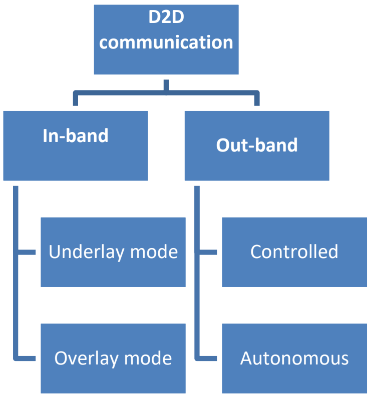

Fig. 1. D2D communication types.

D2D in 5G technology is considered to be two-tier networks[6]: macro cell tier and device tier. While devices in the device tier allow direct D2D communication hence, the base station may have a full or a partial control over the communication among devices. Therefore, both cellular network and D2D are similar and the only difference depends on the fact that the devices at the edges of the cell can perform faithful services we discuss and the devices in the interference areas within the cell. Therefore, both cellular network and D2D are similar and the only difference depends on the fact that the faithful services can be achieved by the devices at the cell edges and the devices in the interference areas within the cell. The devices in device tier allow direct D2D communication hence, the BS may have full or partial control over the communication among devices. Thus, D2D communication in the device tier is categorized into four various types [7]:

- Device relaying with the BS controlling establishment of link.
- Direct communication between devices with the BS controlling link establishment, as depicted in Fig. 2 (our focus).
- Device relaying with the device itself controlling link establishment.
- Direct communication between devices with the device itself controlling link establishment.

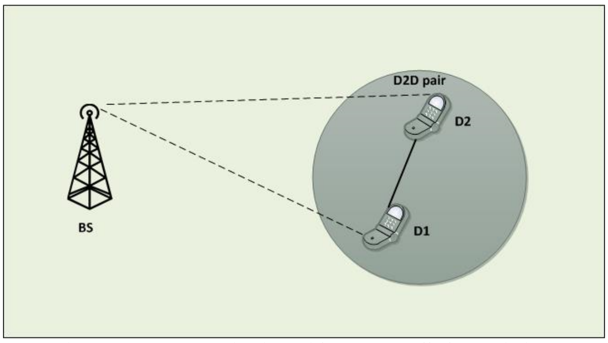

Fig. 2. D2D communication with BS-controlled negotiation.

To overcome the need for high power in cellular networks and the long distance between devices, some amount of traffic needs to be offloaded from the BS and the distance needs to be restricted between devices. Hence, D2D communication performs such a role.

In our paper, we analyze the performance metrics, throughput and delay for device users under the given cellular user activity model and study the effect of different parameters that cause variation such as the number of C_U. We utilize a CSMA based MAC protocol that uses a dedicated common control channel (CCC) to negotiate a data channel between a pair of D_U. The throughput and delay are calculated based on that the D_U can exploit the cognitive radio to access different data channels at the same time in the common interference area.

Moreover, the priority queueing model M/G/C is used to analyze the delay and the C_{Us} are grouped into a high priority queue whereas, the D_{Us} are grouped into a low priority queue. The two queues are served using CH servers priority queue is served only if the number of C_U is less than the number of channels. It is observed that the throughput of D_U is dependent on the C_U traffic and the aggregated throughput of a D_U is improved by more than 60% compared to the individual D2D throughput. This is because the simultaneous transmissions of D_U using CSMA based MAC protocol and the delay is also minimized.

The rest of the paper is structured as follows: Section II presents the motivation for this study and related works. In section III, we introduce our system model. Section IV analyzes the throughput and delay, and section V outlines the performance results and discussion. Finally, the conclusion and future recommendations are provided in section VI.

II. MOTIVATION AND RELATED WORKS

A. *Paper Contributions*

One of the main solutions for overcoming the problem of spectrum scarcity can be cognitive radio. A major issue with cognitive radio is that it needs to take into account the dynamic allocation of channels, which can degrade the quality of service (QoS) and increase transmission with high delay. Therefore, to improve network throughput and spectral efficiency, it is necessary to provide a higher service quality of channels. For channel mobility, it takes more time to spent searching for another available channel which is considered another performance issue (delay) need to be solved in 5G networks.

The delay measurement is formulated using queueing system. We are therefore motivated to analyze the throughput and delay in 5G networks using D2D communication according to the above information.

The main contributions of this paper are that we propose to apply the cognitive radio capability in overlay D2D communication in cellular networks to exploit the unused spectrum of cellular users using concurrent transmissions and the contention between device users is solved using CSMA-based MAC protocol. The overlay D2D communication is applied in this paper where the distance between device users with one hop is higher than a given threshold distance, and the devices communicate with each other with link control established by the BS. In the context of a given cellular user C_U traffic model, we analyze performance metrics such as throughput and delay for D2D users using MATLAB and introduce the relationship between various dynamic parameters. Furthermore, a CSMA-based MAC protocol is used to help CCC negotiate data channels selection between D2D users. To the best of our knowledge, our model is the first model that exploits cognitive-based overlay D2D communication in 5G networks using a CSMA-based MAC protocol with a DC to enhance throughput and reduce delay.

B. Related Works

Fifth generation cellular networks have been an area of interest for many studies, and at this time there is no exact definition for them. Researchers emphasize that achieving the objective of 5G requires heterogeneous networks with multi tiers. One of the important objectives of 5G is increasing the network capacity to meet the rise in mobile data traffic[8]. In previous generations of wireless transmission, D2D communication was less important, but with 5G networks, it is expected to gain much more importance in the upcoming years. It is assumed that 5G networks will have many characteristics that are not effectively met by 4G such as a higher capacity, a higher data rate, better device connectivity, shorter delays, minimal costs, and consistent QoS [9]. Several D2D communication studies have been proposed, with consideration for different metrics such as spectral efficiency, network capacity, QoS, energy efficiency, bandwidth, and delay.

The authors in[10] have proposed a technique to split the transmission rate and classify the message into two parts: public and private. In the public part, the message is decoded by any destination, but in the private part, the message is decoded by the destination itself. The authors analyzed the rate splitting and demonstrated by numerical simulation that the proposed rate splitting increases cell throughput by up to 65% more when the D2D devices are far from the BS and near each other. In [11], the researchers discuss the mode selection problem for D2D in LTE-A cellular networks and utilize channel measurements from the users to estimate the transmission rate. By simulation, their proposal increases system throughput by up to 50% compared to traditional cellular communication.

In[12], the authors have proposed a virtual infrastructure method using nodes to improve system capacity and coverage. All nodes near the BS or within its range are considered relay nodes, depending on the network constraints and traffic requirements. Nodes close to one another are grouped, and the BS serves these groups based on a round-robin scheduling policy to minimize interference using Monte Carlo simulation techniques for both the uplink and downlink. Simulation suggests that the throughput of cell-edge users can be increased from 150% to 300%, and coverage can also be enhanced with significant data rates.

The authors of [13] have proposed a scheduling algorithm to exploit both the random mobility of users and the time-varying channel in cellular networks. The BS broadcasts deadline-based content to different groups. Users in the cell and belonging to the same group communicate directly within their current lists during a contact period. Based on the proposed algorithm, the BS dynamically chooses the number of users to broadcast content to at a given service rate. The simulation results demonstrated that the proposed algorithm can enhance system throughput from 50% to 150%, as compared to one without D2D communications.

The investigators of [15] have implemented D2D communication in cellular networks, taking advantage of orthogonal frequency division multiple access and combining it with distributed scheduling for peer discovery and link management. In [16] cooperation improves the D2D communication quality for data off-loading between the user equipment UEs. The direct links between users are inadequate when the D2D pairs are far away from each other. In this type of D2D communication, the network adaptively decides the communication mode underlay, overlay, or cooperative relay based on the channel quality and data rate requirement. The main issue in cooperative D2D situations is the selection of relay networks, which needs to be efficient when a large number of relays can be used.

In [17], D2D communication based on cognitive and energy harvesting has been modeled. The proposed model was evaluated based on the stochastic geometry, and the researchers reported that the overall QoS of the cellular network is enhanced with cognitive D2D communication. This happens when the network parameters are selected carefully. The authors of [18] have utilized cognitive radios with a CSMA-based MAC protocol but in wireless sensor networks.

In [19], the authors produces analysis of CSMA-based MAC protocol in D2D communication but not in 5G network which will be a heterogeneous network with different bands, and also they utilize Markov process to model the system operation.

In our work we apply cognitive radio in overlay D2D communication in 5G network as a heterogeneous network and analyze the performance metric .

III. SYSTEM MODEL AND ASSUMPTIONS

Our system model and the basic assumptions about cognitive overlay D2D communication mode in a 5G network are explained in this section. In our 5G scenario, a heterogeneous network with different types of services or networks, such as a vehicle network, cellular network, and TV network, each with a BS with licensed bands as well as a Wi-Fi network with an unlicensed band, is considered as shown in Fig.3. The network is assumed to contain two types of users: primary users P_{Us} and device users D_{Us} and the primary user is the owner of the spectrum. The D_{Us} can communicate with each other through or without control of the BS and this depends on a given threshold value ϵ. When the distance between two devices is less than or equal to the threshold value, underlay D2D communication mode is used where the primary and device users are transmitted at the same time on the channels. For example, user D_1 can connect directly with D_2, and vehicle 1 and vehicle 2 also connect directly at the same time due to the distance between them that is less than or equal to ϵ. Otherwise, when the distance between D_{Us} is greater than ϵ., then the devices operate with overlay D2D communication mode with cognitive capability and spectrum sensing is done by the devices themselves and link establishment through the BS. Therefore, both underlay and overlay D2D communication modes will be utilized in our scenario but our focus in this paper is overlay D2D mode. For the latter, the D2D pair cannot communicate directly in the cellular or vehicle network due to the high distance restriction, which will likely cause interference and high power consumption. Hence, we propose that cognitive radio capability be used in this mode to select the unused channel from other bands (licensed or unlicensed) not the cellular band itself, such as Wi-Fi or a TV band, for communication.

We also assume that the device users (D_{Us}) are not equipped with multiple transceivers and do not have accurate knowledge of the network. In addition, the data channel DC is dedicated to the D_{Us} and also the C_U have more privilege of the spectrum than D_U therefore, the D_U senses the presence of the C_U transmissions dynamically and use CCC opportunistically and switch to the idle channel of the C_U transmissions. The network is also assumed to contain Y number of device users D_{Us} who are deployed within a communication range of R meters in a given area. The D_U is modeled in traffic based on the Poisson process and with an arrival rate λD_U. We also assume X number of cellular users C_U, with activity modeled as exponentially distributed inter-arrivals. In this model, the cellular user C_U traffic can be modeled as a two state: idle and busy process with idle rate τ_{idle} and busy rate τ_{busy}. A busy state represents the period used by cellular users, and an idle state represents the unused period. Since each cellular user C_U arrival is independent, each transition follows the Poisson arrival process. Thus, the lengths of idle and busy periods (seconds) are exponentially distributed[20].

Since the arrival of C_U to the channel prevents D_{Us} to use the current data channel CH, the D_{Us} utilize a CCC dedicated to negotiating the use of the potential data channel for transmission between them. The CCC also coordinates the contention between devices such that the D_{Us} are aware of their neighbors when using the current channel.

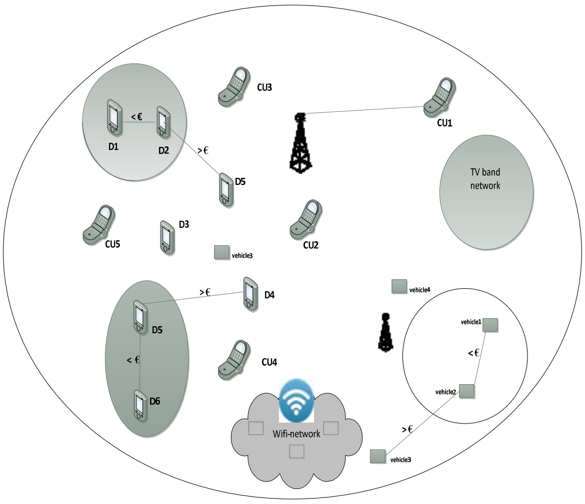

Fig.3: Distribution of different services in a heterogeneous 5G network.

We assume non preemptive D_U transmission and the number of C_U is less than or equal to the number of data channels CH, which are not fully exploited with D_U. Let us also define T_{total}, T_{sens}, and $T_{ovrhead}$ such that T_{total} is the total time of frame period for D_U to transmit the maximum frame size, T_{sens} is the time for sensing, and $T_{ovrhead}$ is the mean overhead time for negotiating the data channel between the D2D pair (the transmitter D_{tx} and receiver D_{rx}), which occur on the CCC beside the CSMA overhead.

While the throughput of the D_U user depends on the arrival rate of C_U, the D_U that uses the CCC for transmission also takes time to transmit on the CCC. Therefore, the total time available for the data frame is therefore as follows:

$$T_{frm}=T_{total}-T_{ovrhead}-T_{sens}$$

D_U can detect its own signal from a C_U transmitter based on the hypothesis model shown below to differentiate between unused and used spectrum band [21]:

$$D_U(t)=\begin{cases} n(t)+C_U(t) & \text{H1 if } C_U \text{ is present} \\ n(t) & \text{H0 if } C_U \text{ is absent} \end{cases}$$

Where n(t) is a zero mean additive white Gaussian noise (AWGN), and both H0 and H1 are the two hypotheses of signal absence (no signal transmitted) and signal presence (signal transmitted), respectively. The output of the received signal process is represented by (y), which is a test statistics for evaluating the two hypotheses H0 and H1 and is later compared with the decision threshold € for deciding whether a primary user exists. From the cellular user activity model, we can estimate the probabilities of busy and idle periods as follows [22]:

$$P_{BUSY}=\frac{Busy}{Idle+Busy} \tag{1}$$

where P_{BUSY} is the probability of the period used by cellular users and P_{Idle} is the probability of the idle period and hence, $P_{Idle} = 1 - P_{BUSY}$. The approximation expression for the probability of detection P_{detct} over AWGN and the probability of false alarm P_{fals} is defined below [22].

$$P_{detct}(€) = P\langle Y > €|H1\rangle P_{Busy} = P_{detct} . P_{Busy}$$

$$P_{fals}(€) = P\langle Y > €|H0\rangle P_{Idle} = P_{fals} . P_{Idle}$$

The presence of C_U is missing when the P_{detct} is low and consequently the interference with C_U increases. Therefore, if P_{fals} is high, the probability of false alarm is high and the number of missed opportunities increases. This leads to a reduction in spectrum utilization.

A. *Proposed System Using a CSMA-based MAC Protocol*

The MAC protocol is employed by D2D pair users (D_U) for medium access negotiation to select the channel that will be used for transmission between D2D pairs. Therefore, we analyze the throughput based on this technique, which is considered a customized version of IEEE 802.11 MAC, and incorporate the dynamic channel switching that the D_U needs. In this proposed technique, the D_U utilizes the CCC to coordinate accessing the data channel among a list of different sensed idle data channels CH. The algorithm is described below.

- When device DU_i wants to transmit to its neighbor, it first runs its spectrum-sensing algorithm, and searches for a vacant channel among a list of channels CH based on lower noise or other factors. Once it finds an idle channel, it stops sensing and sends the result to the medium. We assume the mean sensing period to find a vacant channel is T_{sens}.
- The DU_i adjusts to the CCC and senses the medium to check its availability. If the carrier is busy, the device DU_i runs the exponential back-off algorithm, then waits for the random back-off period.
- If the DU_i finds the channel idle, it waits for a distributed inter-frame space period (DIFS) and sends a request-to-send beacon (C-RTS) including idle data channel CH_i.
- Afterwards, DU_j searches for the availability of CH_i if it is idle among the channel list, or it runs its spectrum sensing algorithm to specify the spectrum's state, which takes T_{sens} seconds. This phase happens after DU_j receives a C-RTS beacon. If DU_j finds the data channel CH_i busy, it will prefer the channel CH_j, and after waiting for a short inter-frame space (SIFS) or sensing time T_{sens} based on the maximum value of SIFS and T_{sens}, it sends a clear-to-send beacon (C-CTS) to DU_i to acknowledge the channel availability of CHi and adjusts to it.
- The DU_i receives C-CTS and checks the notified data channel CH_j. If it finds that $CH_i = CH_j$, it will adjust to CH_i; otherwise, it runs spectrum sensing again for CH_j and repeats the procedure.
- Both devices DU_i and DU_j are now adjusted to data channel CH_i for transmission by DU_i.
- If the channel is sensed idle, DU_i waits for a DIFS period and then transmits a data frame of T_{frm} period; otherwise, it adjusts to the CCC and repeats the procedure for another channel.
- The DU_j waits for an SIFS period, transmits the acknowledgment D-ACK message and adjusts to the CCC after receiving the data frame.
- All devices near the DU_i overhear the C-RTS and do not use the data channel CH_i, which is included in the request beacon. They also overhear C-CTS and do not use the channel CH_j during the transmission for the next frame.
- When a pair of devices (D_U) finish negotiation for the data channel using a CCC, they move to data channel to allow other competing devices to begin negotiation while they are still transmitting. This is illustrated in Fig. 4 below.

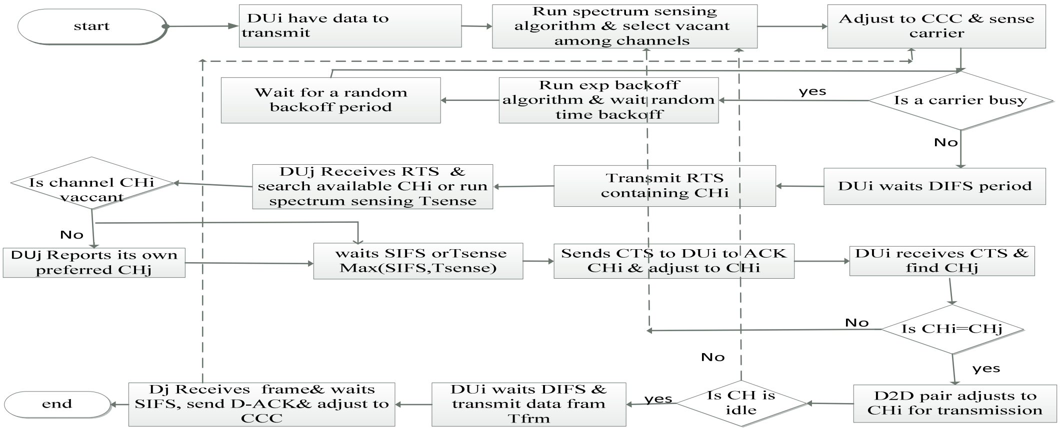

Fig. 4:Flowchart of a customized CSMA-based MAC protocol.

IV. PERFORMANCE ANALYSIS OF A CUSTOMIZED CSMA-BASED MAC PROTOCOL IN OVERLAY D2D COMMUNICATION

We measured the performance of medium access in terms of two metrics; throughput and delay using the CSMA-based MAC protocol in D2D communication in 5G network described in section III.A. To estimate throughput, we computed it for a single D2D pair (D_U) based on the C_U traffic model and then found the aggregated throughput for all D_U by concurrent transmission on different data channels. We also analyzed delay in medium access by conducting priority queueing analysis, and the C_{Us} were assigned the high priority and D_{Us} the low priority. The definition of parameters used in our scenario is listed below in Table1.

Table 1. PARAMETERS AND THEIR DEFINITIONS

Parameters	Definition
rts and cts	The frame delay of RTS and CTS, respectively.
CW_{min}	The minimum value of the contention window
CW_{max}	The maximum value of the contention window
T_{CU_wait}	The waiting time of C_U users
λC_U	The arrival rate of C_U
$\bar{X}$ is the mean number of cellular users C_U	
C_U (t)	The transmitted signal of the C_U.
$D_U(t)$	The signal received by the D_U.
Y_{cmpt}	Number of devices compete for a shared channel

A. Throughput Estimation

In this section, first we estimate the throughput for a single D_U and then for a number of D_U using concurrent transmission on different data channels CH and based on the CSMA MAC protocol. From (1), we find the probability of a channel in busy state for a given C_U traffic model and the probability of a channel in idle state. It is observed that the probability of C_U in busy state increases when the number of C_U increases. Conversely, the probability of busy state decreases when the number of data channels CH increases. Hence, the result is $P_{busy}=(1-P_{idle})^{X/CH}$ where X is the number of device users and CH channels.

Before the D_U begins transmission, the C_U has two cases. The first case is when the C_U is in idle state, in which the false alarm for detecting the received signal $D_U(t)$ of the transmitting C_U does not exist or converges to zero.

Manuscript received February 5, 2024
Manuscript revised February 20, 2024
https://doi.org/10.22937/IJCSNS.2024.24.2.22

We find the signal interference to noise ratio (SINR) for the D_U who is the receiver D_{rx} as follows: $SINR_1 = \frac{D_U}{\eta}$ where η is the noise.

The actual data rate when the channel is detected to be idle is computed as follows:

$$C_1(t) = \mathcal{B} \log_2(1+SINR) \qquad \text{(from Shannon's law)} \qquad (3)$$

$$R_1(t) = (P_{Idle} - P_{detct}) \times \frac{T_{total} - T_{sens} - T_{ovrhead}}{T_{total}} \times C_1(t) \ (4)$$

From the cellular user activity C_U model, it is possible to describe the probability that the spectrum band will be busy throughout the transmission time T as $(e^{-\tau BusyT})$, and the probability of one or more cellular user transitions during T is $(1 - e^{-\tau BusyT})$. When T is relatively short, then during the transmission period T the spectrum state will not change. Therefore, the interference is highly likely to remain with probability throughout the entire transmission period. Nevertheless, when T is long enough, busy and idle states happen alternately during T and interference converges to $(P_{Idle}.T)$ with probability $(1 - e^{-\tau Idle\,T})$.

The second case is when the C_U is in busy state, but the D_U does not detect this due to an error in the spectrum-sensing technique. Hence, we find the SINR ratio for the D_U as $SINR_2 = \frac{D_U}{\eta + C_U}$.

The actual data rate when the channel is falsely detected as being idle is represented by the probability of a channel in a busy state minus that of the probability of the channel falsely detected as idle, $P_{pure} = (P_{Busy} - P_{detect})$ multiplied by the channel capacity:

$$C_2(t) = \mathcal{B}\ \log_2 + \ (1 + SINR_2)$$

(5) (4)

$$R_2(t) = P_{pure} \times \frac{T_{total} - T_{sense} - T_{overhead}}{T_{total}} \times C_2(t)$$

(6)

Hence, we compute the total actual data rate on any channel in both idle and busy states.

$$R_{ovrall} = (1 - e^{-T.CH/\tau Busy\,X}) \times R_1 \ + (e^{-\tau Busy\,T}) \ \times R_2 \qquad (7)$$

We also have average overhead time, which is the time consumed in negotiation of the data channel and also the time used in transmission under the CSMA-based MAC protocol.

We find below also the back-off delay, which is the time the device takes when it finds the channel busy, but its value is changed. Thus, we compute the mean back-off delay $(T_{backoff})$ in a carrier-sensing MAC algorithm as presented in [23].

$$T_{backoff} \sum_{k=1}^{M} P_{succ}(x=K) \times \frac{\left(\min\left(CWmax,\ 2^k CWmin\right) - 1\right)}{2}$$

(8)

Where M is the maximum allowed number of retransmissions before the medium is considered unavailable, and x represents the number of retransmissions suffered by a given frame. The P_{succ} is the probability of a successful transmission of a packet if a number of devices Y_{cmpt} compete for a shared channel in a CSMA MAC technique. The contention window contains a number of w slots in the kth trial as shown in [24]:

$$P_{succ(Ycmpt)} = Ycmpt \sum_{k=1}^{M} \frac{1}{w} \left(\frac{w-k}{w}\right)^{Ycmpt-1} \qquad (9)$$

This means that the sum is multiplied by the number of competitors of the probabilities that a successor selects a certain slot between 1 and w, which is equal to 1/w, and the probability that all the other devices select one from (w − s) later slots. Hence, the mean negotiation delay T_{neg}, which D_U takes on a CCC as an average before starting transmission on the negotiation data channel CH is computed as:

$$T_{neg} = T_{backoff} + DIFS + T_{rts} + SIFS + T_{cts} \qquad (10)$$

As we mentioned before in the CSMA-based MAC section III.A, a D_U adjusts to the data channel and senses the carrier and then waits for another DIFS period before transmission to avoid any interference with transmissions still in progress. The receiver device D_{tx} also waits for an SIFS period before sending the ACK. The overhead time $T_{ovrhead}$ is therefore calculated by $T_{neg} + DIFS + SIFS + T_{ack}$. The D_U overhears RTS or CTS through the negotiation process and does not utilize the negotiation channel in the next transmission. However, the interference between devices is decreased. Thus, when these D_{Us} want to use the same channel, then either they delay their transmission or adjust to a different unused channel.

The D_U can simultaneously transmit on the data channels if $(T_{neg} < DIFS + T_{frm} + SIFS + T_{ack})$ and when the number of any available channels exists and can be chosen with a pair of devices independently. Then the probability of the number of competing device users $Y_{cmpt,}$ and number of channels CH is $e^{-Ycmpt/CH}$. It depends also on the probability of the non-blocking of the CCC negotiation to data channels. The blocking probability is calculated as $P_{block} = \frac{T_{neg}}{DIFS + SIFS + T_{frm} + T_{ack}}$, and for the non-blocking, it is

$P_{non\text{-}block} = (1 - P_{block})$. Thus, the achievable aggregated throughput performed by a pair of competing devices Y_{cmpt} is computed as follows:

$$R_{aggreg} = \sum_{i=1}^{\frac{Ycmpt}{2}} R_{ovrall}\, e^{-\frac{i}{CH}}\ P_{non\text{-}nblock}$$

(11)

B. Delay Estimation

We analyzed the delay in cognitive overlay D2D communication using a queueing system with two queues, one for device user queue (DUQ) with low priority and the other for cellular user queue (CUQ) with high priority. We assumed that the number of servers in the system is equivalent to the number of channels, and any server can serve any queue. Hence, the DUQ can be served only when the channel is empty of C_U, otherwise, the contention still exists. Let us also define T_{que}, T_{neg}, and TD_U as the packet waiting time spent in the queue for accessing the data channel, the waiting time in the channel contention to negotiate the data channel, and the transmission time on the data channel or average service time, respectively. We also assumed that there are enough channels available for every pair of competing devices D_U or the number of competing devices is less than or equal to the number of channels.

Fig. 5 below illustrates the model for the queuing system in overlay D2D communication with cognitive capability. A first come, first served (FCFS) system is used for the packets that arrive according to the Poisson process, whereas the packet service time is exponentially in the CSMA MAC protocol. We use the model M/G/C system to analyze the delay, and CH is the number of channels(servers).

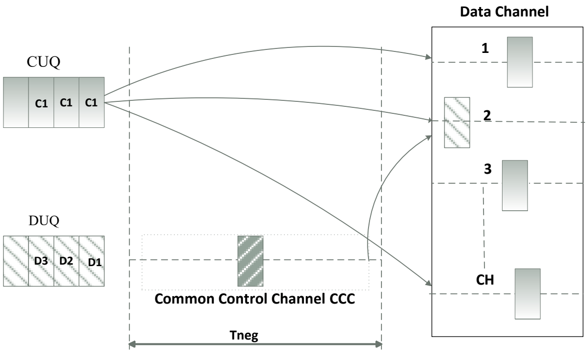

Fig. 5. Queueing model of D2D communication to analyze the delay.

There are no transmission opportunities for D_{US} unless the C_U signal is weak or the probability of missed detection is high. This happens when the C_U is in busy state with period τ_{busy}. Hence, the D_U waiting time when the CUQ contains C_U users over various data CH channels is the busy state probability multiplied by the busy period ($P_{busy \times \tau_{busy}}$). When the C_U has to wait for D_U to complete its transmission T_{frm} after starting, the waiting time for the C_U in the CUQ is computed as follows:

$$T_{CU\_wait.} = T_{frm} + \frac{TC_U \, \overline{X}}{CH} \tag{12}$$

Where $\overline{X}$ is the mean number of cellular users C_{Us}.

By using the little theorem from [25], we have $\overline{X} = \lambda C_U \times T_{CU\_wait}$ and after calculations and substitution, we thus obtain the following equation:

$$T_{CU\_wait.} = \frac{T_{frm}}{1 - UC_U} \tag{13}$$

where UC_U is the utilization factor of channels for C_U and equal to $T_{CU}\ \lambda C_U / CH$.

Our interest is the delay of D_U hence, we have the waiting time for subsequent arrivals in the CUQ. We can therefore introduce the following time in delay. The D_U waiting time in the DUQ is computed as:

$$T_{DU\_wait.} = T_{neg} + (TD_U \times \overline{Y}) + (TC_U \times \overline{X}) + (UC_U \times T_{CU\_wait}) \tag{14}$$

where TD_U is the D_U service time and equal to the following:

$$TD_U = T_{sens} + DIFS + T_{frm} + SIFS + T_{ACK} \tag{15}$$

The waiting time is when the D_U accesses the data channel concurrently after negotiating on the CCC and using the little theorem and substitution in (14). In addition, as previously mentioned, the number of competing devices Y_{cmpt} is less than or equal to the number of channels CH. Thus, the achievable delay for device users D_{Us} to transmit concurrently on different data channels after the negotiation is finished is as follows:

$$T_{DU\_wait.} = \frac{T_{CU\_wait}\ T_{CU} \lambda C_U + T_{neg}}{1 - T_{DU\_wait}\, \lambda C_U \times Y_{cmpt} - T_{CU} \lambda C_U} \tag{16}$$

By substitution where $UC_U = T_{CU}\ \lambda C_U / CH$ and $UD_U = T_{DU}\ \lambda D_U$ it yields:

$$T_{DU\_wait.} = \frac{UC_U T_{CU\_wait.} + T_{neg}}{1 - UD_U * Y_{cmpt} - UC_U} \tag{17}$$

From the above equation, it is observed that the delay for device users D_{Us} is based on data channel utilization by the C_U and the negotiation period for accessing the data channel.

V. RESULTS AND DISCUSSION

In this section, we present and discuss the performance analysis of our scenario for the two metrics, throughput and delay. We compute the throughput for a single D_U using (7) and then calculate the aggregated throughput for a number of D_U using (11) depending on the C_U activity model. We use different parameters for D_U and C_U, as illustrated in Table 1, unless other parameters are mentioned later to analyze the performance of the customized CSMA-based MAC protocol using MATLAB.

Table 1. PARAMETERS USED IN OUR SIMULATION

Parameters	Value
Number of cellular users CU	20
Number of D2D users DU	20
Bandwidth of data channel β	1 MHz
CU mean idle state period	0.5 sec
CU mean busy state period	0.5 sec
Maximum frame period Tfrm	0.5 sec
Number of data channels (CH)	20
Mean arrival rate of DU	0.5 sec

A. Throughput Scenarios

We estimate the throughput for both single and multiple D_U situations. We perform the simulation for an individual D_U throughput by varying frame period T_{frm} at different state periods of C_U (τ_{idle} and τ_{busy}). In Fig.6 below, the individual D_U throughput is computed by changing the values of frame period T_{frm} at various values of C_U idle state periods (τ_{idle}). It is observed that a D_U throughput initially increases when the frame period T_{frm} increases and reaches a maximum value of 0.2s, but it decreases afterwards with the rise in T_{frm} based on the C_U idle state period. This is due to the smaller idle state period (τ_{idle}) causing more interference between C_U and D_U transmissions. Thus, the throughput is not affected more when T_{frm} values increase. The decreasing trend depends on the larger values of idle period. Additionally, in the single device user throughput calculation, the CSMA MAC protocol is not utilized in the data channel, assuming that all D_U devices are aware of data channel usage via overhearing the state of the channel on the CCC.

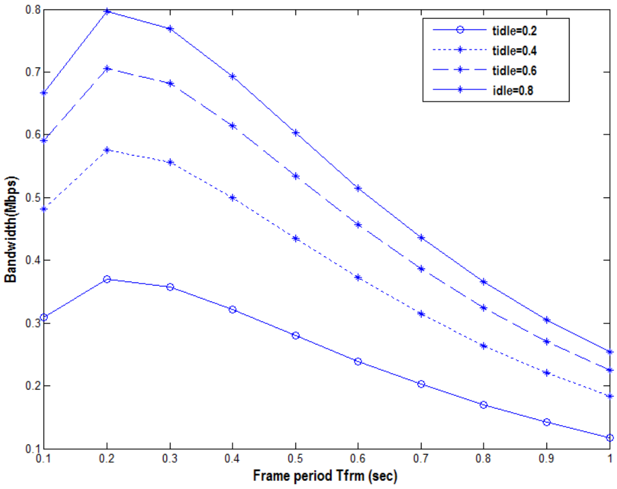

Fig. 6: Throughput of a single D_U pair, where tbusy = 0.5 s, X = 20, CH = 20, and Ycmpt = 15.

In Fig.7 below, we vary the idle state period t_{idle} at different state period t_{busy} to obtain the aggregated throughput of D_U in the common interference range. It can be observed that the aggregated throughput increases linearly with an increase in the value of t_{idle} at higher t_{busy} values of 1s and 0.75s, while it is represented as an exponential at lower t_{idle} values of 0.25 s and 0.5 s. The aggregated throughput is approximately 60% greater than the individual D_U throughput. Hence, using the concurrent transmissions of many D_U by the CSMA-based MAC protocol for negotiating the DC to exploit the spectrum efficiently.

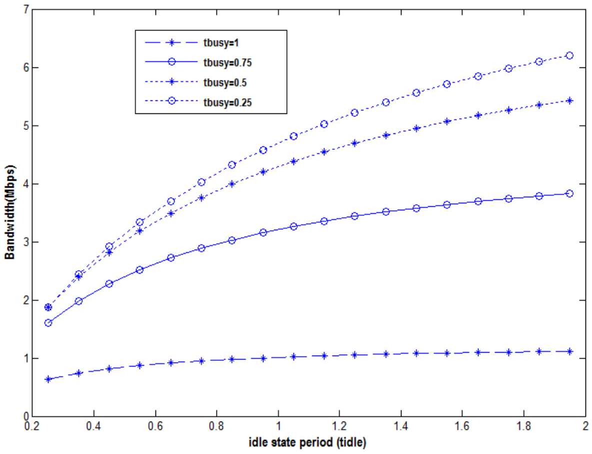

Fig. 7. Aggregated throughput of DUs when varying tidle, where X = 20, CH = 20, Ycont = 15, and Tfrm = 0.5 s.

In Fig.8, we vary the busy state period t_{busy} at different state period τ_{idle} and it is observed that it results in a throughput trend that contrasts with that observed in Fig.7. This is because the busy state period t_{busy} of C_U increases, which leads to a lower probability of $C_U$users being active. Consequently, the D_U has fewer opportunities to transmit on the channels, and the throughput is decreased accordingly. The spectrum is also utilized efficiently due to D_U using multiple transmissions simultaneously when the channels are negotiated using the CSMA MAC protocol on the CCC.

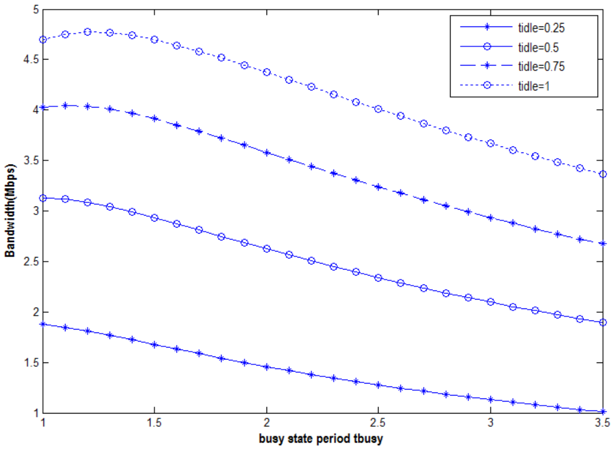

Fig. 8. Aggregated bandwidth(throughput) of DUs when varying tidle, where X = 20, CH = 20, Ycmpt = 15, and Tfrm = 0.5 s.

Fig.9 studies the effect of the number of D_U users in the interference area at various values of frame period T_{frm} on the throughput. It is observed that the aggregated throughput increases significantly with the number of D_U increases. This is due to a growth in the number of transmissions by D_U, which take the opportunities to transmit and to sense. Moreover, the throughput peaks after half of the interval at a large frame period T_{frm} value. In addition, exploiting the cognitive capability to form channel to channel dynamically takes place in improving the aggregated throughput.

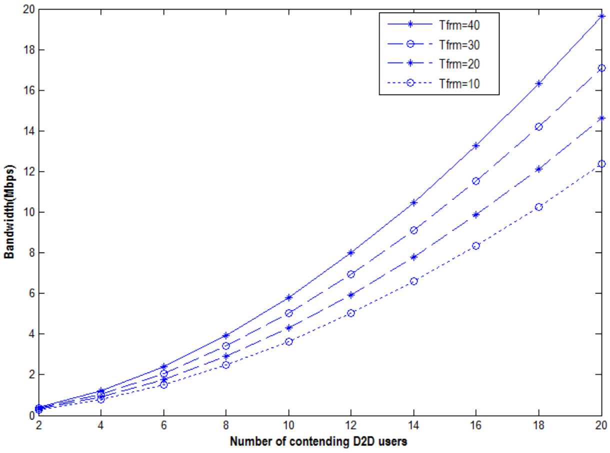

Fig. 9. Aggregated bandwidth(throughput) with varying number of DU in the interference area (Ycmpt), where X=20 and CH=20.

B. Delay Scenarios

We evaluate access to different channels in cognitive overlay D2D communication and conduct the simulation in various traffic scenarios for a number of channels using (17). In Fig.10, we vary the number of C_U at different values of frame period T_{frm} for D_U to analyze the delay. When the frame period is shorter, the service rate is higher, which consequently reduces the CUQ waiting time for C_U. As the number of C_U increases, the corresponding waiting time of C_U rises, and therefore the delay increases linearly at higher values of frame period T_{frm}.

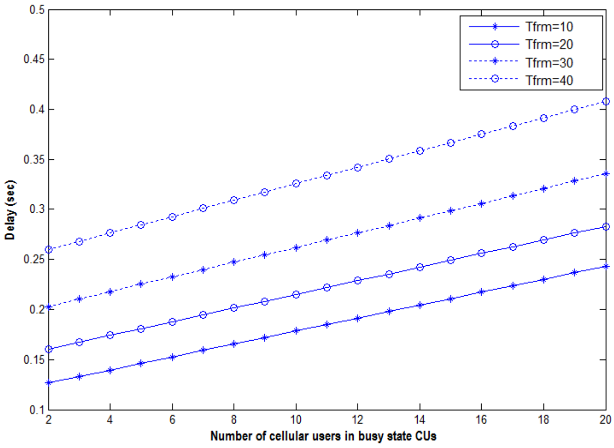

Fig. 10. Delay of packet for DUQ by varying the number of CU, with values tidle = 0.5, tbusy = 0.5 s, Ycmpt = 10, and CH = 20.

In Fig.11, we analyze the effect of C_U activity on D_U packet delay by varying the C_U busy state period at different frame periods. It is observed that delay increases exponentially at higher values of τ_{busy}; it also rises after half of the interval, especially at frame period T_{frm} values of 20s, 30s and 40s. Keeping the frame period T_{frm} of D_U small decreases delay by improving the service rate of the DUQ. This is important when the number of C_U is larger.

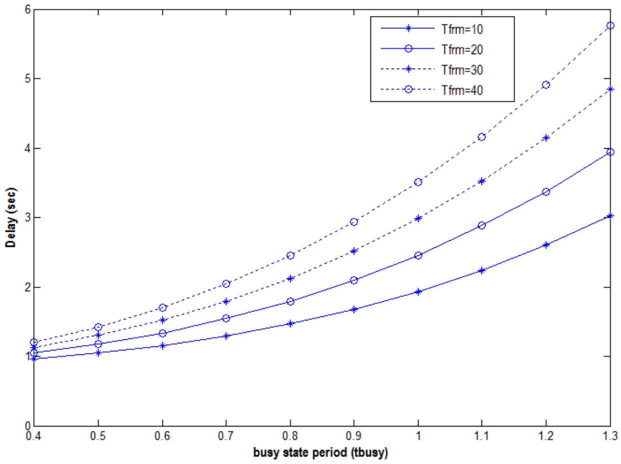

Fig. 11. The packet delay of DU with changing CU busy period, where tidle = 0.5 s, X = 20, CH = 20, and Ycmpt = 10.

VI. CONCLUSION

In this paper, we investigate the potential of applying the cognitive radio capability using concurrent transmissions on different unused channels in overlay D2D communication in 5G network. We formulate the two performance metrics, throughput and delay for device users $\mathrm{D}_{\mathrm{U}s}$ under cellular user activity model and study the relationship between various parameters and C_{U} activity model. We utilized a CSMA-based MAC protocol beside a dedicated common control channel to negotiate using a data channel among a pair of D_{U} . It is observed that the aggregated throughput can be approximately 60% higher than the individual D_{U} throughput by employing a direct connection between devices and exploiting the cognitive capability for the unused spectrum as well as by allowing simultaneous transmissions on different channels. Coordination between devices was done using CSMA based MAC protocol to address the. Finally, we hope to analyze underlay D2D communication using a CSMA-based MAC protocol with shared resources for cellular and D2D users to enhance 5G network performance in our future research.

References

[1] T. Turinawe and I. Mukonyezi, “DEVICE TO DEVICE COMMUNICATION IN 5G TECHNOLOGY,” no. August, 2017.

[2] O. Nait Hamoud, T. Kenaza, and Y. Challal, “Security in device-to-device communications: a survey,” *IET Networks*, vol. 7, no. 1, pp. 14–22, 2018.

[3] N. Panwar, S. Sharma, and A. K. Singh, “A survey on 5G: The next generation of mobile communication,” *Phys. Commun.*, vol. 18, pp. 64–84, 2016.

[4] P. Gandotra and R. K. Jha, “Device-to-Device Communication in Cellular Networks: A Survey,” *J. Netw. Comput. Appl.*, vol. 71, no. 4, pp. 1801–1819, 2016.

[5] R. I. Ansari *et al.*, “5G D2D Networks: Techniques, Challenges, and Future Prospects,” *IEEE Syst. J.*, vol. 12, no. 4, pp. 3970–3984, 2018.

[6] U. N. Kar and D. K. Sanyal, “An overview of device-to-device communication in cellular networks,” *ICT Express*, vol. 4, no. 4, pp. 203–208, 2018.

[7] A. S. Khan, Y. Javed, J. Abdullah, J. M. Nazim, and N. Khan, “Security issues in 5G device to device communication,” vol. 17, no. 5, pp. 366–375, 2017.

[8] V. Shrimali and A. Gaur, “A Review on Communication Infrastructures in 5G Cellular Networks,” vol. II, no. Ii, pp. 94–98, 2015.

[9] A. Gupta, S. Member, R. K. Jha, and S. Member, “A survey of 5G network: Architecture and emerging technologies,” *IEEE access*, vol. 3, 2015.

[10] C. H. Yu and O. Tirkkonen, “Device-to-device underlay cellular network based on rate splitting,” *IEEE Wirel. Commun. Netw. Conf. WCNC*, pp. 262–266, 2012.

[11] Z. Liu, T. Peng, S. Xiang, and W. Wang, “Mode selection for Device-to-Device (D2D) communication under LTE-advanced networks,” *IEEE Int. Conf. Commun.*, pp. 5563–5567, 2012.

[12] K. Vanganuru, S. Ferrante, and G. Sternberg, “SYSTEM CAPACITY AND COVERAGE OF A CELLULAR NETWORK WITH D2D MOBILE RELAYS Outline • Background • D2D Mobile Relays • High Level Concepts • System Model • Performance Results • Conclusions,” 2012.

[13] H. Cai, I. Koprulu, and N. B. Shroff, “Exploiting Double Opportunities for Latency-Constrained Content Propagation in Wireless Networks,” *IEEE/ACM Trans. Netw.*, vol. 24, no. 2, pp. 1025–1037, 2016.

[15] Y. Wu, W. Liu, S. Wang, W. Guo, and X. Chu, “Network coding in device-to-device (D2D) communications underlaying cellular networks,” *IEEE Int. Conf. Commun.*, vol. 2015-September, no. July, pp. 2072–2077, 2015.

[16] Y. Cao, T. Jiang, and C. Wang, “Cooperative device-to-device communications in cellular networks,” *IEEE Wirel. Commun.*, vol. 22, no. 3, pp. 124–129, 2015.

[17] A. H. Sakr and E. Hossain, “Cognitive and Energy Harvesting-Based D2D Communication in Cellular Networks: Stochastic Geometry Modeling and Analysis,” *IEEE Trans. Commun.*, vol. 63, no. 5, pp. 1867–1880, 2015.

[18] G. A. Shah and O. B. Akan, “Performance analysis of CSMA-based opportunistic medium access protocol in cognitive radio sensor networks,” *Ad Hoc Networks*, vol. 15, pp. 4–13, 2014.

[19] H. N. Abdulrazzak and A. A. Hussein, “Performance Analysis of CSMA/CA Based on D2D Communication,” no. March, 2019.

[20] M. Wellens, J. Riihijärvi, and P. Mähönen, “Modelling primary system activity in dynamic spectrum access networks by aggregated ON/OFF-processes,” *2009 6th IEEE Annu. Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Networks Work. SECON Work. 2009*, 2009.

[21] F. F. Digham, M. S. Alouini, and M. K. Simon, “On the Energy Detection of Unknown Signals Over Fading Channels,” *Commun. IEEE Trans.*, vol. 55, no. 1, pp. 21–24, 2007.

[22] W. Y. Lee and I. F. Akyildiz, “Optimal spectrum sensing framework for cognitive radio networks,” *IEEE Trans. Wirel. Commun.*, vol. 7, no. 10, pp. 3845–3857, 2008.

[23] M. Mi, “On the Capacity of p -Persistent CSMA,” Int. J. Comput. Sci. Netw. Secur., vol. 7, no. 11, pp. 38–43, 2007.

[24] H. Zhao, E. Garcia-Palacios, J. Wei, and Y. Xi, “Accurate available bandwidth estimation in IEEE 802.11-based ad hoc networks,” *Comput. Commun.*, vol. 32, no. 6, pp. 1050–1057, 2009.

[25] J. D. C. Little, “ A Proof for the Queuing Formula: $L = \lambda W$,” *Oper. Res.*, vol. 9, no. 3, pp. 383–387, 1961.