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A High Throughput Device-to-Device Wireless Communication System

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SUMMARY Device-to-device (D2D) communication in cellular networks is defined as direct communication between two mobile users without traversing the base station (BS) or core network. D2D communication can occur on the cellular frequencies (i.e., inband) or unlicensed spectrum (i.e., outband). A high capacity IEEE 802.11-based outband device-to-device communication system for cellular networks is introduced in this paper. Transmissions in device-to-device connections are managed using our proposed medium access control (MAC) protocol. In the proposed MAC protocol, backoff window size is adjusted dynamically considering the current network status and utilizing an appropriate transmission attempt rate. We have considered both cases that the request to send/clear to send (RTS/CTS) mechanism is and is not used in our protocol design. Describing mechanisms for guaranteeing quality of service (QoS) and enhancing reliability of the system is another part of our work. Moreover, performance of the system in the presence of channel impairments is investigated analytically and through simulations. Analytical and simulation results demonstrate that our proposed system has high throughput, and it can provide different levels of QoS for its users.

key words: *device-to-device communications, capacity enhancement, quality of service, network architecture*

1. Introduction

We have observed rapid development of wireless communications and networking over the last two decades. Widespread use of cellular networks and wireless local area networks (WLANs) are examples of this development. D2D communication has been introduced to provide out-of-coverage communication, and also to enhance resource utilization (e.g. in terms of spectral efficiency) [1]–[5] in cellular networks. It enables two neighboring mobile devices to use a direct local link for data transmission. The mobile devices may communicate directly with each other over D2D links while remaining under control of the BSs.

D2D users can communicate both in licensed and unlicensed spectrum. When D2D communication and cellular communication take place at the same frequency range (e.g. licensed spectrum), interference between users of these two categories of communication should be coordinated. Various techniques have been proposed recently to reach this

objective [6]–[8]. A system for sharing resources between D2D users and cellular users is introduced in [6]. An interference management strategy for enhancing the capacity of cellular networks and device-to-device systems is proposed in [7]. The authors in [8] have developed a distributed dynamic spectrum protocol in which ad-hoc device-to-device users opportunistically access the spectrum actively in use by cellular users.

Management of packet transmissions in unlicensed spectrum can be done using the IEEE 802.11 distributed coordination function (DCF) [9]. The idea of enabling D2D wireless communication for handling local traffic can be seen in works such as [10]–[12]. The authors in [10] have proposed the Unified Cellular and Ad Hoc Network (UCAN) architecture for enhancing cell throughput while maintaining fairness. In UCAN, a mobile client has both third-generation (3G) interface and IEEE 802.11-based peer-to-peer links. The 3G base station forwards packets for destination clients with poor channel quality to proxy clients with better channel quality. The proxy clients then use an ad hoc network composed of other mobile clients and IEEE 802.11 wireless links to forward the packets to the appropriate destinations. However, although proxy discovery and ad hoc routing for D2D communication is introduced in [10], throughput degradation of the IEEE 802.11 DCF resulted from growth of network users is not considered in this work. In [12], Multihop Cellular Network (MCN) is proposed to enhance the system throughput and limiting the path vulnerability of ad hoc networks. Wi-Fi Direct is also a technology defined by the Wi-Fi Alliance [13] aimed at enhancing direct device to device communications in Wi-Fi. Similar to legacy Wi-Fi networks, performance of Wi-Fi Direct is prone to degradation when the number of contending nodes increases. Other recent related works can be seen in [14]–[22].

Another research topic related to IEEE 802.11-based D2D ad hoc wireless communication is MAC layer protocol capacity improvement. Several MAC layer protocol capacity enhancement techniques for IEEE 802.11 standard exist in the literature [23]–[29]. These techniques include introducing delay before transmission of packets, dynamically adjusting backoff window size, reservation of slots, and cross-layer design of protocols. However, most of the works in this area do not consider the stability issues of wireless network in their designs.

In this paper we introduce an outband D2D wireless

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communication system for cellular networks. Device-to-device ad hoc communication takes place at the unlicensed spectrum, and it is managed by a high throughput MAC protocol based on the IEEE 802.11 DCF. High capacity of MAC protocol is obtained by tuning the minimum contention window size (CW_{min}) of stations considering network configuration. Moreover, stability of mean access delay of nodes is considered in our protocol design. Base station and mobile devices have different responsibilities which will be described as follows. Base station of cellular network is responsible for tuning CW_{min} in different channel conditions in order to have a QoS-aware high capacity MAC protocol. BS can guarantee different levels of QoS for different users by providing various amounts of minimum contention window sizes. Mobile devices should utilize the CW_{min} provided by BS in their packet transmissions. It should be noted that our mechanism for design of MAC layer protocol parameters can be applied to other existing technologies for D2D communications utilizing 802.11 DCF such as WiFi Direct. Through analysis and extensive simulations, we evaluate the throughput and the average end-to-end delay for the D2D communication system. MAC layer protocol performance of our system is compared with the IEEE 802.11 DCF and two other schemes for capacity enhancement of the IEEE 802.11 DCF. Simulation results show that implementing the proposed system architecture can provide a high performance D2D wireless communication system in comparison with other existing similar approaches.

The remainder of the paper is organized as follows. Our proposed system architecture is detailed in Sect. 2. Section 3 includes performance evaluation of the system. Finally, conclusion is drawn in Sect. 4.

2. The Proposed System Architecture

In this section, we introduce the system architecture. In addition to regular cellular network communications, mobile devices should have connections with BS to obtain system parameters for their packet transmissions in D2D mode of operation. D2D communication is performed at unlicensed spectrum, and medium access is coordinated by our proposed MAC protocol. BS is responsible for receiving requests of mobile devices for D2D connections. After receiving a request it should assign an appropriate minimum contention window for the nodes. Mobile devices are required to use this minimum contention window for their transmissions. High capacity MAC layer protocol and quality of service provisioning mechanism are different parts of the communication system which will be detailed in this section. Besides outband cellular D2D systems, the proposed system architecture can be applied to WLANs.

MAC protocol

Our proposed MAC layer protocol is an enhancement of the IEEE 802.11 DCF. CW_{min} is tuned in our protocol with respect to network configuration so that the network throughput is improved. We utilize the mechanism

introduced in [30] for tuning of CW_{min} with a different strategy for choosing the transmission attempt rate and packet length. Based on the model of the IEEE 802.11 DCF introduced in [28], stations transmit their frames with a specific transmission attempt rate in an IEEE 802.11-based network. This attempt rate is different for various network configurations. In fact, it has a larger value for a network with more active stations. The transmission attempt rate depends on the number of active nodes and also their average backoff times. In the IEEE 802.11 DCF that uses binary exponential backoff, when the number of active nodes grows, the average backoff times of the nodes will not grow enough to preserve the value of the attempt rate. These conditions result in the growth of the attempt rate in more populated networks. The attempt rate parameter of an IEEE 802.11 wireless network will be introduced more accurately later. Higher attempt rate in a network leads to a higher collision probability. In our proposed MAC protocol, stations fix their attempt rate to a specific value, and the attempt rate is not increased when the number of active nodes is increased. The mechanism of fixing the attempt rate is described in this part. Also, proper values for the attempt rate are determined for the cases with and without the RTS/CTS mechanism.

Let P_t represent the probability of transmission of a station in a slot time. P_t depends on the behavior of nodes in selecting their backoff intervals in legacy DCF. In this section, we determine a proper value for P_t in order to enhance throughput and stability of the mean access delay of the nodes. Based on the model of Kim and Hou for IEEE 802.11 DCF [28], the transmission probability of a backlogged node (if the channel is sensed as busy before a transmission or if a transmission has a collision, the node becomes backlogged) is determined by a backoff timer. Denoting the number of active nodes in the network by M , the time till the next transmission attempt can be approximated as a random variable with the exponential distribution. The rate of this random variable is known as the transmission attempt rate which depends on the current set of backoff windows. The average attempt rate λ is given as [28]

$$\lambda = M/\bar{b}, \quad (1)$$

where $\bar{b}$ is the average backoff time of stations.

Here, we review some of the necessary equations found in [28]. Average number of collisions between two consecutive successful transmissions $\bar{n}$ is expressed as [28]

$$\bar{n} = \frac{1 - e^{-\lambda} - \lambda e^{-\lambda}}{\lambda e^{-\lambda}}. \quad (2)$$

Let $\bar{x}$ be the average time it takes to successfully transmit a frame, $\bar{c}$ the average length of the collision period, $\bar{c}\bar{w}$ the average number of idle slots before a collision or a successful transmission, DIFS the distributed interframe space, SIFS the short interframe space, and EIFS the extended interframe space. For the case with the RTS/CTS mechanism we have [28]

$$\bar{c} = \bar{c}\bar{w} + t_{RTS} + EIFS \text{ and}$$

$$\bar{x} = \bar{c}\bar{w} + t_{RTS} + t_{CTS} + t_{ACK} + \bar{x}' + DIFS + 3SIFS.$$

Table 1 IEEE 802.11g system parameters

Basic Rate	1 Mb/s
Slot Time	20 μ s
SIFS	10 μ s
DIFS	50 μ s
EIFS	SIFS+Phy preamble & header+tACK+DIFS
Phy preamble	144 bits
Phy header	48 bits
MAC header	224 bits
ACK	112 bits
RTS	160 bits
CTS	112 bits

Also,

$$\bar{c} = \bar{c}w + \bar{x}' + EIFS \text{ and}$$

$$\bar{x} = \bar{c}w + tACK + \bar{x}' + DIFS + SIFS$$

are valid when the RTS/CTS mechanism is not used [28]. $\bar{x}'$ is the average frame length. Considering $\bar{f}$ as the total collision period in a frame service time, we have [28]:

$$\bar{f} = \bar{n}\bar{c},$$

and the expected throughput is given by [28]

$$T = \frac{\bar{x}'}{\bar{x} + \bar{f} + (1/\lambda + DIFS)(1 - \bar{c}w(\bar{n} + 1))}. \quad (3)$$

Our MAC protocol is based on IEEE 802.11g [31], and performs exponential backoff with the same maximum value for contention window (CW) size, as in the standard IEEE 802.11. However, minimum contention window size is determined adaptively. This protocol is described as follows. BS should determine CW_{min} of transmitting mobile devices. It calculates the average backoff time $\bar{b}$ by substituting an appropriate transmission attempt rate (λ) and the number of active nodes in the network (M) in (1). Stations should transmit their pending frames by the probability P_t , obtained from $P_t = 1/(\bar{b} + 1)$, in each slot time till the successful transmission of that frame. For this purpose, after calculating P_t , the average size of contention window is computed from $E[CW] = (2/P_t) - 1$. By considering the discussions for finding the relation between $E[CW]$ and CW_{min} available in [30] and [32], the initial size of contention window is equal to $E[CW]/2^{\log M}$, and using this CW_{min} leads to transmission of frames with the calculated transmission probability. When the calculated initial contention window size exceeds 1024, stations will use 1024 as CW_{min} . CW_{max} is 1024 in our MAC protocol.

The IEEE 802.11g system parameters used in this paper are given in Table 1. The current set of parameters guarantees the compatibility with IEEE 802.11b. Data rate in the system can be more than the basic rate that is 1 Mbps. We have done our computations using a data rate of 54 Mbps.

As we expressed earlier in this paper, nodes are required to fix their average transmission attempt rate. The value of attempt rate has impacts on performance of the system. Therefore, the attempt rate should be chosen carefully. In the remainder of this part, a proper value is determined

Fig. 1 OVRHD versus transmission attempt rate.

for the attempt rate.

After simplifying (3) we have

$$T = \frac{\bar{x}'}{\bar{x} + \bar{f} + 1/\lambda + DIFS(1 - \bar{c}w(\bar{n} + 1)) - \bar{c}w(\bar{n} + 1)}. \quad (4)$$

Substituting numerical values of system parameters in (4) for the case with the RTS/CTS, we can write it as follows:

$$T = \frac{\bar{x}'}{\bar{x}' + 1/\lambda + 23.7\bar{n} + 23.2}. \quad (5)$$

As can be seen from (5), by minimizing $1/\lambda + 23.7\bar{n} + 23.2$ in the denominator of (5), we can obtain the maximum throughput for different frame lengths. We define the parameter $OVHRD = 1/\lambda + 23.7\bar{n} + 23.2$ that is shown in Fig. 1. $OVHRD$ is minimized at an attempt rate of 0.265 (1/slot). However, in addition to minimizing the $OVHRD$, we have considered mean access delay stability when choosing attempt rate of the system.

Based on the model used in this paper, mean access delay of stations is obtained by $\bar{d} = \bar{n}(\bar{c}w + EIFS + tRTS) + \bar{c}w = \bar{n}(1/\lambda + 26.2) + 1/\lambda$, and the Laplace transform of the mean access delay is expressed as

$$D^*(s) = N_c(CW^*(s)CF^*(s)e^{-(EIFS)s})CW^*(s), \quad (6)$$

where $CW^*(s)$ and $CF^*(s)$ denote, respectively, the Laplace transform of the probability density functions associated with CW and CF . CW_i is the random variable denoting the number of idle slots before the i th collision or the successful transmission, and CF is the random variable indicating the size of a collided frame. The distribution of CF is the same as that of X' (the random variable indicating the size of a successfully transmitted frame) and is given. $\bar{x}'$ is the average of X' . N_c is the random variable representing the number of collisions between two consecutive successful transmissions. The z transform of N_c is $N_c(z)$, and we have [28]

$$N_c(z) = \sum_{n=0}^{\infty} P[N_c = n] \cdot z^n = \frac{\lambda e^{-\lambda}}{1 - e^{-\lambda} - (1 - e^{-\lambda} - \lambda e^{-\lambda})z}.$$

Substituting $CW^*(s)$ by $\exp(-s/\lambda)$, where $1/\lambda$ is the average number of idle slots before each transmission attempt, in (6) we obtain

$$D^*(s) = \frac{\lambda e^{-\lambda}}{(1 - e^{-\lambda})e^{s/\lambda} - (1 - e^{-\lambda} - \lambda e^{-\lambda})e^{-26.2s}}. \quad (7)$$

Fig. 2 Distance of the pole from imaginary axis versus transmission attempt rate (RTS/CTS mode).

Fig. 3 $OVRHD_2$ versus transmission attempt rate.

$D^*(s)$ has a real pole in the left region of the s-plane. As can be seen in Fig. 2, maximum distance of the pole from imaginary axis is 0.083 at an attempt rate of 0.1 (1/slot).

To have a balance between low overhead and high stability, we choose 0.18 (1/slot) as the preferred transmission attempt rate of the system. 0.18 (1/slot) is the arithmetic mean of 0.265 (1/slot) and 0.1 (1/slot) where the distance of the pole from imaginary axis is 0.077 at this attempt rate. Selection of 0.18 (1/slot) as the attempt rate, results in CW_{min} of 143 and 271 in networks with 40 and 100 active nodes, respectively.

When the RTS/CTS mechanism is not used, the equation for the throughput is

$$T = \frac{\bar{x}}{\bar{x} + 8.6 + 1/\lambda + 15.7\bar{n} + \bar{n} \cdot \bar{x}} \quad (8)$$

$OVRHD_2 = 8.6 + 1/\lambda + 15.7\bar{n} + \bar{n} \cdot \bar{x}$ in (8) is an indicator of the overhead required for transmission of a frame. Therefore, it is obvious that we should have $\bar{x}$ for minimizing the overhead. We select a typical frame length of 2 KByte for our calculations. $OVRHD_2$ is demonstrated in Fig. 3, and it is minimized at an attempt rate of 0.25 (1/slot).

Mean access delay when the RTS/CTS mechanism is not utilized is obtained from $\bar{d} = \bar{n}(\bar{c}w + EIFS + \bar{x}) + \bar{c}w = \bar{n}(1/\lambda + 18.2 + \bar{x}) + 1/\lambda$. Here, the Laplace transform of the mean access delay is

Fig. 4 Distance of the pole from imaginary axis versus transmission attempt rate (RTS/CTS disabled mode).

$$D^*(s) = \frac{\lambda e^{-\lambda}}{(1-e^{-\lambda})e^{s/\lambda} - (1-e^{-\lambda} - \lambda e^{-\lambda})e^{-(18.2 + \bar{x})s}} \quad (9)$$

Similar to the RTS/CTS case, $D^*(s)$ has a real pole near the origin in the left region of the s-plane. The distance of this pole from the imaginary axis versus attempt rate is demonstrated in Fig. 4, and only has a maximum of 0.069 at an attempt rate of 0.07 (1/slot). Arithmetic mean of 0.07 (1/slot) and 0.25 (1/slot) is 0.16 (1/slot) that is selected as the system transmission attempt rate for the case without the RTS/CTS mechanism. Using this attempt rate leads to a pole with a distance of 0.063 from the imaginary axis. In this case, CW_{min} will be calculated as 166 and 313 for 40 and 100 active nodes, respectively.

Quality of Service

Another issue that can be considered in specifying attempt rate of stations is quality of service. Delay, jitter, and dropping probability are criteria commonly used for measuring quality of service. We have chosen delay as our performance measure for differentiating QoS of users. Based on the relations for mean access delay, we infer that increasing the attempt rate for some stations in a constant $\bar{n}$ can decrease their access delay. In order to have a constant $\bar{n}$, we need to maintain the system aggregate attempt rate, which is the average of attempt rates of all of the active stations, to a constant value. The BS can assign different attempt rates to different users, while preserving the average of attempt rates to the previously specified values, to adjust users' access priority. Consequently, different levels of QoS can be provided for different users. For example, by assignment of the attempt rates of 0.2 (1/slot) and 0.16 (1/slot) to two 5 station groups in a network with 10 stations, we will have two levels of QoS in the network with an average attempt rate of 0.18 (1/slot). The users with higher attempt rates can be selected with respect to concerns such as the urgency of the connection or the billing issues. Succinctly, the BS is able to determine various transmission attempt rates, with the average values specified in the previous part (0.18 (1/slot) and 0.16 (1/slot) for the cases with and without the RTS/CTS, respectively), for users with different levels of QoS by sending them the CW_{min} , corresponding to a particular attempt

rate, calculated using the mechanism explained in the MAC layer protocol description. The value of CW_{min} is lower for a higher λ which leads to a lower backoff time and access delay. When the delay is chosen as the performance measure for QoS differentiation, the attempt rate for various groups of mobile nodes can be specified based on the assessment of the mean access delay obtained by $\bar{d} = \bar{n}(1/\lambda + 26.2) + 1/\lambda$, when using the RTS/CTS, and $\bar{d} = \bar{n}(1/\lambda + 18.2 + \bar{x}') + 1/\lambda$, when not using the RTS/CTS. Simulation results in the next section confirm the applicability of this approach for QoS provisioning.

As can be observed from Eq. (2), higher attempt rate in the network can increase the number of collisions between two consecutive successful transmissions ($\bar{n}$). When there are some high priority connections in the network (e.g. in urgent conditions), the BS can assign a very high attempt rate to them. However, assignment of a high attempt rate to some of mobile devices without significantly reducing the attempt rate of other devices can lead to a large $\bar{n}$. For instance, when we have 10 stations with an average attempt rate of 0.16 (1/slot) and $\bar{n}$ of 0.084, increasing the attempt rate of 2 of these stations to 0.32 (1/slot), without decreasing the attempt rate of other stations, results in a network with an average attempt rate of 0.192 (1/slot) which leads to an $\bar{n}$ of 0.1. However, in the previous case, by decreasing the average attempt rate of other 8 stations to 0.12 (1/slot), the average attempt rate of the network will be maintained to 0.16 (1/slot) that makes $\bar{n}$ intact. If we desire to have a proper $\bar{n}$, we can initially set the attempt rate of the network to a value slightly lower than previously determined values. Therefore, assignment of a high attempt rate to some users can not greatly influence the total average of the number of collisions in the network, and as a result, we have a more reliable network.

3. Performance Evaluation

This section includes analytical and simulation results. We have used the iterative method introduced in [28] for calculating the attempt rate in different network configurations (for a network that uses the legacy DCF). As we stated previously, attempt rate is set to a particular value in our proposed MAC protocol. Normalized system throughput is obtained analytically using Eq. (3). Results are shown in Fig. 5. Frame length is set to 2 KByte while the data rate is 54 Mbps. Based on this figure, the proposed method keeps its throughput regardless of M by selecting an appropriate size of contention window for M nodes. The analytical results shown in Fig. 5 for the proposed MAC protocol are obtained by substituting the attempt rates of 0.18 (1/slot) and 0.16 (1/slot) specified for the cases with and without the RTS/CTS mechanism, respectively, in (3). Because the attempt rate is constant for all M in both cases, the straight lines are acquired. However, in a system that operates with the legacy DCF, the attempt rate is variable for different values of M . The λ s derived using the iterative method depend on CW_{min} and M , and their values are

between 0.9 (1/slot) and 1.98 (1/slot) for M between 10 and 100 ($CW_{min} = 16$). Consequently, the throughput of the legacy DCF is variable for various values of M . Figure 5 demonstrates that the throughput of 802.11 DCF is degraded when M increases. It can be observed from Fig. 5 that the throughput enhancement obtained by the proposed system is at least 17.86 percent and 62.07 percent when using and not using the RTS/CTS mechanism, respectively. Also, the throughput enhancement is incremented for larger M in both cases.

In the remainder of this section, we present simulation results on the network simulator *ns2* [33]. Mobile nodes are moving in a 500 m $\times$ 500 m area (the nodes are initially distributed randomly with a uniform distribution), and the random waypoint model is considered as their mobility model. Pause time is 60 sec when minimum and maximum speeds are 0 and 20 m/sec, respectively, in the mobility model. Also, we use the two-ray-ground as the radio propagation model. No Ad-Hoc Routing Protocol (NOAH) [34] is used for single-hop routing. Basic rate and data rate are 1 Mbps and 54 Mbps, respectively, in our simulations. The simulation time is set to 2000 sec where the results are averaged over 10 simulation rounds conducted with various random seeds.

As previously mentioned, there are various schemes for improving performance of an 802.11 DCF-based D2D wireless communication system. We have chosen MFS [28] and AOB [24] schemes for comparison with our proposed MAC protocol. In MFS, each node keeps track of the number of collisions between its two consecutive successful transmissions and the time interval between its two successful transmissions. It then determines the number of currently active nodes, calculates the network utilization with the throughput model used in this paper, and computes a scheduling delay by which it will not access the wireless medium. AOB is proposed for runtime optimization of 802.11 DCF in the case without the RTS/CTS mechanism. Using the method described in [24], we calculated the transmission probability of stations for the related network configurations and frame sizes. Throughput of our proposed MAC protocol is compared with IEEE 802.11g, MFS, and AOB in Figs. 6 (a) and 6 (b). CBR/UDP (constant bit rate/user datagram protocol) traffic with a rate of 500 Kbps is sent between each pair of nodes. Each node sends traffic to another node and receives traffic from the same node. Frame size is 2 KByte in the cases with and without the RTS/CTS mechanism. As can be seen from Fig. 6, our proposed MAC protocol significantly outperforms 802.11 DCF and performs better than MFS and AOB. Throughput enhancement achieved by using the proposed MAC protocol, as compared with IEEE 802.11g, is up to 48 percent in the current settings (with and without the RTS/CTS). Also, the throughput of AOB is better than MFS, and both of these schemes are successful in enhancing the throughput of standard IEEE 802.11 DCF. Analytical and simulation results of throughput evaluation have been demonstrated in Figs. 5 and 6, respectively. To obtain the normalized throughput for simulations, the simulation re-

Fig. 5 Normalized throughput versus the number of active nodes (analytical results). (a) With the RTS/CTS mechanism. (b) Without the RTS/CTS mechanism.

Fig. 6 Throughput versus the number of active nodes (simulation results). (a) With the RTS/CTS mechanism. (b) Without the RTS/CTS mechanism.

sults should be divided by the data rate (54 Mbps). The normalized analytical results are derived using the model for binary exponential backoff introduced and verified in [28]. In simulation study, there are factors that can lead to the difference between the normalized analytical and simulation results. These factors include mobility of the nodes, power saving and beaconing functions of the MAC protocol, and also problems related to routing in an ad hoc network [28]. A reason for lower throughput in a sparser network (a network with smaller M) that can result in the ascending throughput curve of Fig. 6 is that it is more probable in such networks that the stations cannot find their destinations in their transmission range depending on the network area, radio propagation model, pause time, and velocities of the nodes. In addition, the referred model is based on the approximation $(1 - P_t)^M \approx e^{-MP_t}$ in large enough M . Therefore, we can observe in Fig. 6 that for smaller values of M (where the approximation is not accurate enough), the throughput curve is ascending while the analytical results show a straight line. The difference between the simulation results and the analytical results for relatively large values of

M is due to the limitations of the model in analyzing the effects of factors such as interference and hidden/exposed station problem on the throughput of the system. When M increases, the number of hidden and exposed terminals in the network is increased which causes a higher collision probability, and as a result, the throughput is decreased. Moreover, the throughput degradation caused by interference is greater in a more populated network. Although these two factors also affect the throughput in smaller M , their effect is not great enough to change the throughput curve to a descending one for these values of M .

The average end-to-end delay for various situations can be observed in Table 2. The improvement in end-to-end delay for the case with the RTS/CTS is 2.4 percent, 11.33 percent, and 12.81 percent for M of 10, 50, and 70, respectively. For the case without the RTS/CTS, the improvement in end-to-end delay is 13.82% and 16.32% for M of 50 and 70, respectively. Performance degradation in $M = 10$ is due to the selected attempt rate which is lower than the attempt rate of 802.11 DCF. In RTS/CTS mode, the enhancement obtained with the proposed system in 100 and 500 stations

Table 2 Average end-to-end delay (msec)

	$M = 10$	$M = 50$	$M = 70$	$M = 100$	$M = 500$
802.11g with RTS/CTS	6457.4	40222.3	48182.6	80338.8	108860
Proposed MAC with RTS/CTS	6304.6	35665.4	42010.2	69408.9	97834.3
802.11g without RTS/CTS	99.8	22684.4	27591.2	35710.7	69179.8
Proposed MAC without RTS/CTS	139.3	19549.2	23087.1	32551.9	59670.7

Table 3 Average delay variation (msec)

	$M = 10$	$M = 50$	$M = 70$	$M = 100$	$M = 500$
802.11g with RTS/CTS	1010	4870	4261	3086	12338
Proposed MAC with RTS/CTS	632	3263	3669	2052	10697
802.11g without RTS/CTS	136	4900	5882	2156	7381
Proposed MAC without RTS/CTS	194.1	2221	2953	1175	5500

is 13.6% and 10.13%, respectively. The average end-to-end delays for 100 and 500 stations without the RTS/CTS show an enhancement of 8.84% and 13.74%, respectively. When the number of nodes increases in the area, due to the limitations in the frequency resource which depends on the density of the nodes, the delay improvements reach the ceiling. In the current settings, we have delay enhancement with the proposed MAC protocol up to 510 and 503 nodes in a $70 \text{ m} \times 70 \text{ m}$ area for the cases with and without the RTS/CTS mechanism, respectively. Consequently, the delay enhancement is achievable in a network with a node density of up to approximately $0.1 \text{ (node/m}^2\text{)}$.

The average of variations in delay (known as jitter) is shown in Table 3. The jitter for the RTS/CTS case is decreased from 13.3 percent to 37.42 percent by using the proposed MAC protocol. The improvement obtained in the case without the RTS/CTS mechanism is from 25.48 percent to 54.67 percent. Using the results of Tables 2 and 3 for M less than 100, it can be deduced that the jitter is from 8.84 percent ($M = 70$) to 15.64 percent ($M = 10$) of the end-to-end delay by using 802.11 DCF with the RTS/CTS mechanism. By using the proposed MAC protocol, the jitter is from 8.73 percent ($M = 70$) to 10.02 percent ($M = 10$) of the end-to-end delay. When the RTS/CTS mechanism is not used, the jitter is 21.6 percent and 21.32 percent of the end-to-end delay for M of 50 and 70 (802.11 DCF), respectively, and by utilizing the proposed MAC, the jitter ranges from 11.36 percent and 12.79 percent of the end-to-end delay for M of 50 and 70, respectively. The results shown in Table 3 indicate enhancement in relatively large values of M (100 and 500 nodes). These are other enhancements obtained by using the proposed MAC protocol.

When the number of nodes increases, some extra overhead on control information, including request messages from the nodes and the contention window information, has to be paid; the appropriate contention window allocation can improve the transmit efficiency for the data traffic. When the mobile nodes have the feature of the static or low mobility, the contention window information can keep unchanged within a long time interval and thus the overhead on control information will be negligible [35]. Because most of the data transmission coordination takes place in a distributed manner using the proposed MAC protocol and the amount

of control traffic is relatively low, growth of the number of active nodes does not significantly affect the performance of the system. The performance of passing control traffic depends on the implementation. If the control traffic passes through a channel with unlicensed spectrum (e.g. an 802.11-based network), the performance of passing the control traffic may decrease by about 40 percent (by variation of the number of nodes from 10 to 100) [28]–[30]. If the implementation is such that there were dedicated channels between the BS and the mobile nodes under the control of a long term evolution (LTE) system, considering the results of [36], the system will not be affected so much by growing the number of mobile nodes in a high signal to interference and noise ratio (SINR) (over 25 dB). In medium values of SINR, W_{eff} (set as 0.57), as the attenuation factor, that accounts for link level implementation overhead and also for overhead due to pilot, and control channel signal can be applied to the Shannon bound for capacity of the dedicated channel [36]. Finally, in low SINR (under -10 dB), control traffic transmission is not feasible. More details can be observed in [36].

Investigating the effectiveness of our mechanism for providing different levels of QoS is another part of our simulation study. There have been different approaches toward QoS differentiation and its evaluation in the literature [37]–[41]. In this study, we evaluate the end-to-end delay for three categories of nodes with different attempt rates (low, medium, and high) with approximately the same number of nodes in each category. By setting the same number of nodes in each category, we prevent the influence of nodes with a specific attempt rate on nodes with other attempt rates. In such conditions, comparison of delay for various categories is more meaningful. The total attempt rates of the networks are 0.18 (1/slot) and 0.16 (1/slot) by the following settings as specified for the cases with and without the RTS/CTS mechanism, respectively, in Sect. 2, and we can observe the effect of varying attempt rate on different categories of nodes. There are 100 active nodes in the network. CBR/UDP traffic rate is 64 Kbps. In the RTS/CTS mode, 33 nodes have an attempt rate of 0.08 (1/slot) ($CW_{min} = 488$), 33 nodes have an attempt rate of 0.18 (1/slot) ($CW_{min} = 217$), and the remaining nodes have an attempt rate of 0.28 (1/slot) ($CW_{min} = 140$). Average

end-to-end delays for these three categories of nodes are 137726 msec, 38048 msec, and 20841 msec, respectively. In the case without the RTS/CTS, 33 nodes have an attempt rate of 0.06 (1/slot) ($CW_{min} = 650$), 33 nodes have an attempt rate of 0.16 (1/slot) ($CW_{min} = 244$), and the remaining nodes have an attempt rate of 0.26 (1/slot) ($CW_{min} = 151$). In this case, average end-to-end delays for the three categories are 161238 msec, 27962 msec, and 13721 msec, respectively. These results show that our QoS provisioning mechanism is successful in providing different levels of QoS for different users.

4. Conclusion

In this paper, we introduced a D2D wireless communication system in which the transmissions are coordinated using a MAC protocol based on the IEEE 802.11 DCF. Our designed system has higher protocol capacity in comparison with the legacy DCF. This capacity enhancement is achieved by tuning the backoff window size of stations with respect to the network configuration. We determined proper values for the attempt rate of mobile nodes in the cases with and without using the RTS/CTS mechanism. Different levels of QoS can be provided for different users through specifying suitable attempt rates. In addition to the theoretical analysis, performance evaluation of the proposed MAC protocol is carried out through simulations. The simulation study showed that our proposed MAC protocol for D2D communication exhibits high performance in comparison to legacy DCF and other existing proposals for improving performance of 802.11 DCF. Extension of the proposed MAC protocol for using in a multi-hop scenario can be the subject of future research.

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