A Clustering-Based Device-to-Device Communication to Support Diverse Applications

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ABSTRACT

In this paper, we address the issue of how to leverage Wi-Fi Direct (as an outband solution) to enable the Device-to-Device (D2D) communication that can offload massive data traffic from the LTE (Long Term Evolution)-based cellular network and support other applications. Particularly, we develop a clustering-based scheme that automatically finds the best candidates to remain connected to the LTE network while the rest of the devices can be disconnected directly from the LTE-based cellular network. By doing so, we can reduce the signal interference, increase the average throughput and spectral efficiency of the network, and also reduce unnecessary data traffic that can be transmitted locally by D2D communications instead of going through the LTE-based cellular network. Devices in established clusters can indirectly communicate with the LTE network via the cluster head, which can be dynamically selected and remains connected to the LTE network directly. Using the real-world cellular data collected from a public database related to the deployment of LTE networks, we show the effectiveness of our proposed scheme in traffic offloading in the cellular network. We also discuss how to use our developed techniques to support Internet-of-Things (IoT) applications such as smart grid communications.

CCS Concepts

•Networks → Wireless access points, base stations and infrastructure; Network performance evaluation; Mesh networks; Mobile networks; Network mobility; Peer-to-peer networks; Wireless access networks; Network architectures; Network algorithms;

Keywords

Device-to-Device Communication; Clustering; Traffic Offloading; Applications

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1. INTRODUCTION

Generally speaking, D2D communication refers to a technology that empowers devices (User Equipments (UE), smart meters, sensors, etc.) to send and receive data directly without going through the core wireless network infrastructure via base stations (or access points) [3]. The D2D communication can be either inband or outband. Inband refers to the case where the D2D communication utilizes the same spectrum that devices use to communicate to the base station, while the outband D2D communication refers to the case where the spectrum used for D2D communication does not coincide with the one used by base station communication. Wi-Fi Direct [1] is one known outband D2D communication technology, which operates at Industrial, Scientific and Medical (ISM) radio bands. Notice that the question of how to effectively share spectrum resources and overcome interferences from devices (UE, smart meters, sensors, base stations, etc.) remains a challenging issue in inband D2D communication.

In this paper, we focus on the investigation of the outband D2D communication technique and demonstrate its feasibility by offloading traffic in cellular networks and supporting other applications. Our paramount contributions are listed as following.

First, we outline our developed clustering-based scheme to enable the D2D communication for devices that are close to each other. In this way, massive traffic can be transmitted via D2D communication in local areas and traffic transmitted via the core cellular network can be reduced. The main idea behind the clustering scheme is to create small Wi-Fi networks for communications between devices in local areas while these devices remain connected indirectly to the cellular network via the head of the clusters. Within each cluster, the cluster head directly connects to the LTE network and is dynamically selected based on various factors (quality of reception, bandwidth, etc.).

Second, having implemented Wi-Fi Direct as an outband solution for enabling D2D communication within a simulated LTE network, we demonstrate the effectiveness of our scheme via a case study: offloading traffic in the cellular network as an example. We leverage the Vienna LTE-A system level simulator [12][1] and have collected real-world deploy-

[1]Certain commercial equipment, instruments, or materials are identified in this chapter in order to specify the experimental procedure adequately. Such identification is not

ment information of base stations via OpenCellID website [5]) to demonstrate the effectiveness of our proposed scheme. The experimental data shows that our developed scheme can be used to significantly improve the network performance by offloading traffic in the cellular network. Our proposed scheme is generic, and can be applied to support other types of wireless networks and other applications. We discuss how to use our developed scheme to extend the performance improvement to smart grid communications.

The remainder of the paper is organized as follows: We introduce the background and related work in Section 2. In Section 3, we present our schedule in detail. In Section 4, we show the experimental results to validate the effectiveness of our proposed scheme in offloading traffic in the cellular network. We conclude the paper in Section 5.

2. BACKGROUND AND RELATED WORK

In this section, we give the background and related work of D2D communication and Wi-Fi Direct.

2.1 D2D Communication

D2D communication in LTE networks refers to directly routing data traffic among mobile User Equipment (UEs) when UEs are close to each other. By doing so, network performance measured by energy efficiency, throughput, delay, as well as spectrum efficiency can be improved. Such a communication technique has been considered as a viable solution to deploy the cellular network infrastructure in rural areas, support public safety applications when the network infrastructure breaks down during a disaster, and support the monitoring and control of numerous applications (smart grid, etc.). For example, in a public safety application, when a disaster strikes, the mobile devices of emergent response personnel can directly communicate with each other via D2D communication so that the data traffic on the wireless network raised by growing traffic demands can be offloaded, or in the event that wireless infrastructure is not even available.

There have been a number of research efforts on developing D2D communication techniques to improve the spectral efficiency of wireless networks [9, 4]. Sharing a widely used spectrum in the cellular network (also called inband D2D communication) can be problematic because of the interference between the communication spectrum used for both D2D communication and cellular communication. Notice that the inband D2D communication in cellular networks requires additional efforts and changes to the components of cellular networks. Also, how to efficiently manage the shared spectrum allocated for D2D communication remains an open issue. In contrast, because the cellular network uses a different spectrum from the D2D communication, interference will not occur.

With respect to outband-based D2D communication techniques, unlicensed spectrum is commonly used for supporting the communication of D2D links. In these techniques, while no interference issue exists between D2D communication and cellular communication, mobile devices are normally required to have an extra wireless communication interface to support the different wireless communication implementations (Wi-Fi Direct [6, 2], ZigBee [13], Bluetooth [10], etc.) through an unlicensed spectrum.

2.2 Wi-Fi Direct

Wi-Fi Direct is a Wi-Fi standard, which tends to enable wireless devices to easily connect with each other without the support of wireless access points [1]. Wi-Fi Direct can negotiate the link with a Wi-Fi management system, which assigns each device a wireless Access Point (AP) (known as Software Access Point (Soft AP)). By using Soft AP, a Wi-Fi Direct-enabled device becomes multi-role, hosting small networks and clients of other Wi-Fi networks, and supports multi-hop communication. By using multi-hop technology in Wi-Fi Direct-enabled networks, the coverage of a small local network can be easily extended by adding another device to the network. The throughput of Wi-Fi Direct-enabled networks can be enhanced due to shorter communication hops required to send and receive data. In addition, the battery life of devices will be extended due to low power for data transmission between nearby devices even though the destination of the data is far away.

In our proposed clustering-based scheme in Section 3, we assume that all UEs support Wi-Fi Direct and every cluster is a Wi-Fi Direct network with a mesh-based topology to support multi-hopping data transmission. Also, after clustering and selecting the head of the cluster, every cluster is connected to the cellular network via the head of the cluster.

3. CLUSTERING-BASED D2D SCHEME

In this section, we first give an overview of our clustering-based D2D scheme and then present the detailed design and workflow of our proposed scheme.

3.1 Overview

To reduce the traffic overload in the network and improve the bandwidth efficiency, D2D communication is an effective solution to offload traffic from the cellular network and utilize the network resources more efficiently. Recall that in this paper, we consider the use of Wi-Fi Direct as an outbound solution to provide D2D communication, which requires fewer changes in the LTE-based cellular network. By using Wi-Fi Direct and transmitting data locally among nearby mobile users, we can offload data traffic from the cellular network and prevent interference to cellular users as the Wi-Fi Direct and cellular network operate in different frequency bands. By doing so, the available bandwidth for each mobile user can be increased by offloading the local data traffic from the global cellular network. The local data can be transmitted in a multi-hop manner in Wi-Fi Direct networks, where each UE requires a low transmission power to send and receive data, via a multi-hop fashion even when the source and destination of the data are significantly far away in the same Wi-Fi Direct network.

The D2D communication in a mesh-based Wi-Fi Direct network (denoted as cluster) not only provides improved coverage because of multi-hop data forwarding, but also enhances the throughput of the network due to shorter hops and extend battery life because many users and meters are located nearby each other. Nonetheless, if any UE requires data to be transmitted globally, the head of the cluster in the Wi-Fi Direct network can provide the communication to the cellular network indirectly based on the Wi-Fi direct network that it is already connected to.

intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

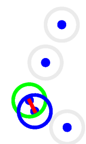

Figure 1: Discovering Neighbours (Discoverer UE in Blue, Neighbours in Range in Green, Out-of-Range Neighbours in Grey)

To enable the D2D communication in the cellular network, we propose a clustering-based scheme, which creates clusters for small Wi-Fi Direct networks. All the UEs within each cluster can directly and indirectly communicate with each other and transfer data without necessarily going through the core cellular network. In each cluster, the node that remains directly connected to the cellular network is the head of the cluster, which is dynamically selected based on the quality of reception, bandwidth, and other factors. In the following, we explain how the clustering-based scheme gathers the statistical data, creates the clusters, merges the clusters, and then selects the heads for clusters.

3.2 Cluster-Based D2D Communication

The main idea behind the proposed clustering method is to enable the local D2D communication so that each UE can communicate with other UEs based on established small mesh-based Wi-Fi networks dedicated for D2D communication among UEs while these UEs remain connected indirectly to the LTE network via the head of the cluster. In each cluster, the node that remains directly connected to the LTE network is defined as the head of the cluster, which is dynamically selected based on the quality of reception, bandwidth and other metrics.

Our developed clustering scheme consists of the following steps:

Step 1. Discovering devices and finding the nearest neighbours: The first step gives UEs that have the Wi-Fi Direct capability a way to discover each other, as well as services that they support. For example, a UE with Wi-Fi Direct capability can see all compatible devices in a given area and then narrow down the list of devices that enable the Wi-Fi Direct D2D communication. Mobile users can decide whether to join the clustering service or not by turning the service on and off on their UE. In the simulation tool that we used [12], as there was no Wi-Fi Direct feature provided, we have implemented a module to define the Wi-Fi range for each UE and perform the discovery. We assume that all discovered UEs are willing to join the D2D-based communication based clusters created. To simulate the Wi-Fi discovery process and obtain a list of available neighbours for each UE, we create a discovery list that can store up to 256 neighbours for each UE. As shown in Figure 1, every neighbour is listed in each UE record only when it is located within the Wi-Fi range of the current UE. The discovery list is generated based on the distance between the current UE and their neighbours, considering the maximum Wi-Fi range given prior to the simulation.

Step 2. Creating clusters for D2D communication: Once the UE that has not joined a cluster has generated a list of discovered nearby devices using the Wi-Fi Direct discovery service, the clustering process begins. Every UE starts from the beginning of the discovery list and creates a new cluster of its own if the UE and its neighbours in the discovery list have not already been assigned to one cluster. Otherwise, every UE will join all the clusters it finds in the discovery list that its neighbours have already connected to. For example, if UE_1 has three UEs (UE_2, UE_3 and UE_4) in its discovery list and none of them has yet joined any cluster, the UE_1 will create a new cluster and allow its three neighbours to join. On the other hand, if any of the three UEs (say UE_3) has already connected to a cluster, UE_1 will not create a new cluster, but instead will join all of the same clusters as its neighbors. By doing so, the UE can join multiple clusters at a same time. Then, later in the merging process, all clusters that are sharing UEs will be merged and become one cluster.

Step 3. Merging clusters: When a UE is joined to more than one cluster, all those clusters could be merged into one cluster. By broadcasting the cluster information, it is possible to let the head of each cluster know that a new UE has joined multiple clusters. Then, the head of clusters can proceed another round of the head election process and one of them becomes the head of the newly formed merged cluster. Figure 2 illustrates an example of merged clusters in regions. As we can see from this example, the Wi-Fi coverage of every UE is portrayed in green circles. Wherever these circles intersect each other, a cluster is created and starts to grow until there are no more circles close enough to expand the cluster any more. In one case, several small clusters could be created inside another cluster and those clusters remain unmerged as there is no UE in between to connect these clusters.

The clustering-based D2D communication in the cellular network needs to be periodically updated due to the fact that mobile users could change their locations dynamically. As a result, the selection process of the new head of cluster needs to be conducted periodically. Since UEs are mobile, they may lose connection from one cluster and join another cluster. Consequently, the clustering and role changing operations must be performed continuously for each cluster as well. On one hand, two or more clusters may be merged because of those clusters are close enough. On the other hand, one cluster could be broken into two or more clusters because UEs may go far enough as a group (or alone) to lose connection from the original cluster and then create their own clusters. In addition, even in some cases there may be a few small clusters (inner clusters) created inside a larger cluster (outer cluster) as the inner clusters cannot reach any of UEs associated with the outer cluster. In Figure 3, we show a black arrow pointing to an inner cluster that cannot merge with the outer cluster unless some of UEs from either inner or outer clusters move toward the UEs from another cluster and make a D2D connection available. Once this bridge connection is established, the inner cluster will merge into the outer cluster.

Step 4. Indirect LTE connection: To reduce the data traffic load of the cellular network, the local data traffic associated with UEs can be transmitted via D2D communications within the clusters. Since we do not want to completely remove the UEs from the LTE network, we select one of the UEs in each cluster that is denoted as the head of the cluster, which remains connected to the LTE network. In each D2D cluster, only the head of the cluster remains connected to both the cluster and cellular network directly. Every other node within the cluster can indirectly connect to the cellular

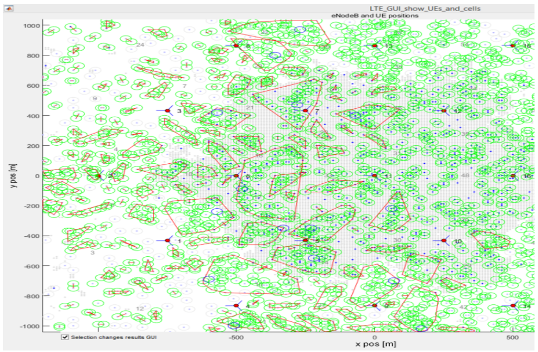

Figure 2: Merged Clusters

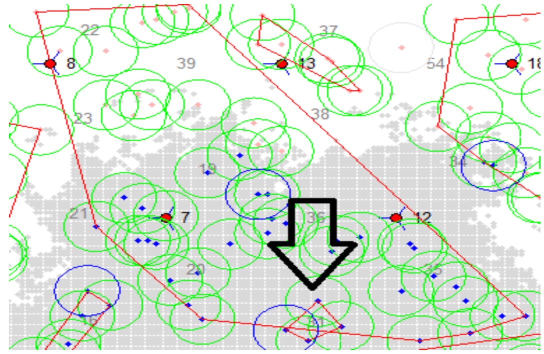

Figure 3: Out of Range Clusters Not Merged

network through the head of the cluster, which functions as a relay node. Notice that the communication between the cluster member and the cluster head may be a direct link between them or through multiple one-hop links.

Step 5. Changing cluster head: At the beginning of the cluster head selection process, each UE considers itself the head of the cluster. Nonetheless, there might be another UE inside the same cluster that has better connecting characteristics. In this case, the head of the cluster will be changed to the latter UE. The re-election process of cluster heads is a periodic process that gathers the statistical information about all UEs connected to a single cluster. At the end, the best candidate will be selected to be the next head of the cluster. To make the selection, the statistical information about signal quality, coverage, and other factors can be obtained via the network. The re-election process of cluster heads can be controlled by the service provider via the cellular network, or be autonomously completed inside the cluster by the head of the cluster. The maximum average throughput and maximum average spectral efficiency are two major factors that the re-election process is based on.

Our proposed scheme produces additional clusters and later merges them due to the fact that each UE only sees the other UEs under its own Wi-Fi coverage at the beginning. By joining other clusters, the heads of the clusters will find out that they are now connected to each other and can merge down and release one of the heads (known as "chaining phenomenon", in particular with the single-linkage clustering [7]). Notice that the complexity of our proposed clustering scheme is $O(n^3)$, where n is the number of UEs.

Due to the fact that the proposed scheme is implemented as part of an LTE network simulator, it sees the UEs from the network perspective. The complexity of this method of implementation is much higher in comparison with running the proposed scheme on each UE individually, where each UE only sees the nearby UEs, making the complexity much lower and computation more efficient. In other words, instead of doing the clustering on the LTE network side, we can let the UEs carry out the clustering themselves in parallel and then let the LTE network know the structure of clusters. This information can be later provided for the LTE network by the heads of clusters for relaying data between LTE and Wi-Fi direct networks.

From the network operation perspective, there are two types of D2D communications: controlled and autonomous. The former is under the supervision of the cellular network, and the latter is totally independent. Although we use the controlled type in our implementation, in order to reduce the complexity and share the computation power required between the UEs, our proposed clustering scheme can be implemented with the autonomous type of D2D clustering as well, which is independent from the cellular network and uses the UEs computation power to reduce the computation power needed, and let the UEs carry out the clustering themselves independently.

3.3 Supporting Other Applications

Our proposed scheme is generic and can support diverse applications. Particularly, IoT has attracted significant attention and can be considered to a networking infrastructure which can connect massive amounts of physical objects belonging to numerous critical infrastructure systems and others. For example, in the smart grid, the geographically distributed meters, sensors, actuators and controllers are tightly integrated through communication networks and computational cores, enabling the secured and efficient operations of the power grid [8, 14, 15]. We can leverage our developed clustering-based scheme to establish mesh-based Wi-Fi Direct networks to connect smart meters (sensors) in the smart grid. Then, the head of a cluster will provide indirect communication links between meters (sensors) in the cluster and the operation center, either through the cellular network or by connecting to another nearby cluster.

We have collected real-world data for both eNodeBs and UEs from OpenCellID (similar to the Case Study in Section 4) and smart meters (as UEs) from Google. For the eNodeBs, we need to define a ROI to obtain the first 1000 tower locations and for the smart meters, we need to generate complete postal addresses to obtain the locations of the smart meters one by one. To use real-world data for smart meters and bring them to the simulation, we used Google geo-coding APIs and generated HTML "get" requests in Matlab simulation code to gather the locations of the smart meters. Since the exact locations of smart meters that are actually installed are not available to the public, we use the locations of the addresses that we gather from Google geo-coding APIs and assume they already installed a smart meter. In the implementation, those coordinates of addresses are converted to a two dimensional map using built-in functions in Matlab that receive latitude and lon-

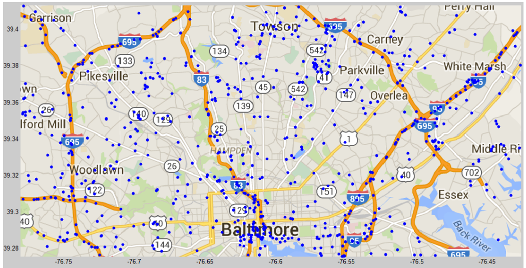

Figure 4: Site Locations of Baltimore City Area

gitude and translate them into a 2D position to show on a 2D map (also gathered from Google). Due to limited space, the detail evaluation of supporting other applications can be found the extended version of the paper.

4. CASE STUDY: TRAFFIC OFFLOADING IN CELLULAR NETWORKS

To show the effectiveness of our proposed scheme in the application case of offloading traffic for cellular users, we leverage the Vienna LTE-A system level simulator [12] and collected the real-world deployment information of base stations via the OpenCellID website [5] to carry out our performance evaluation.

Evaluation Setting: In our simulation, we generate LTE cells in a honeycomb structure and UEs are randomly deployed throughout the cells. To make our study to reflect the real-world practice, we have implemented a tool to obtain the deployment information of base stations from cellular network providers (AT&T, Verizon, T-Mobile, etc.) and have established realistic cellular networks to carry out the performance evaluation.

To measure the effectiveness of Wi-Fi Direct-based D2D communication on the realistic LTE-based cellular network, we consider the performance metrics, including average UE throughput, average spectral efficiency, and UE wideband Signal to Interference and Noise Ratio (SINR). Generally speaking, the throughput can be computed in symbols per second. The downlink spectral efficiency of the communication system can be measured in Bits Per Channel Use (bpcu) [11]. SINR, as the measurement of signal quality, can be used to quantify the relationship between RF conditions and throughput in the experimented network. By comparing metrics in the case without enabling D2D communication to the case with D2D communication, we can observe the improvement of performance of our proposed scheme based on these metrics.

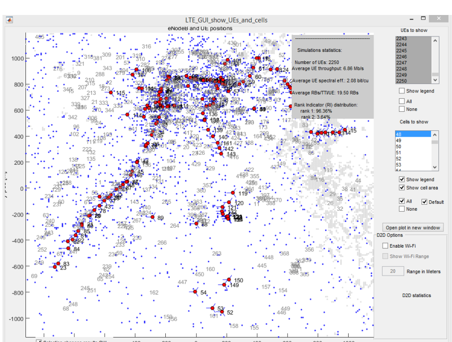

Figure 5: 150 Site Locations

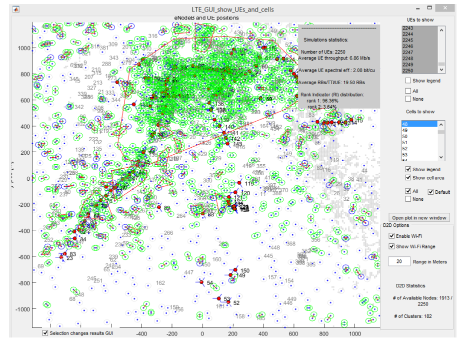

Figure 6: Clusters of 150 Sites

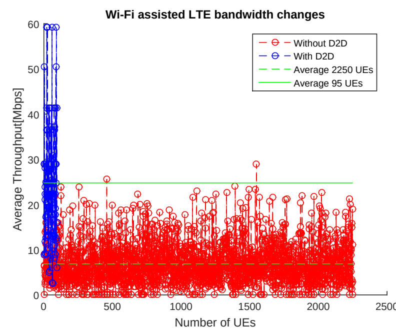

Figure 7: Average Throughput of UEs

Real-World Data Collection: To use the real-world data for the location of each eNodeB, we have retrieved the site locations from an open worldwide database called OpenCellID [5]. This website provided APIs for making HTTP (Hypertext Transfer Protocol) requests in different formats, e.g., XML (Extensible Markup Language) and Comma Separated Values (CSV). Based on the Region Of Interest (ROI), we can define the intended location and retrieve 1000 site locations in each HTTP request. As an example, we have retrieved the locations of eNodeB in Baltimore city, the state of Maryland. Figure 4 shows 1000 eNodeBs.

In our simulation, we choose the first 150 site locations from Baltimore city area and these site locations in the list downloaded from the online database point to highway 695, Pikesville, and Parkville as shown in Figure 5. In our simulation, we use these locations of eNodeB and randomly generate 2250 UEs to run the simulations. After applying our developed clustering-based D2D communication scheme, we create clusters for randomly deployed UEs. Figure 6 shows an example of merged clusters for UEs in the simulated area.

Evaluation Results: We run the simulation for both the LTE only communication and Wi-Fi Direct assisted LTE using our proposed method to create clusters. Figure 7 shows a magnificent increase in the average throughput of UEs when the D2D communication is used. As we can see from Figure 7, the number of clusters (blue curve) was 95 (182 clusters merged down to 95) and 1913 UEs out of 2250 were able to join clusters, while the rest of the UEs were out of range. Each cluster has one UE (head of cluster), which connects to the LTE network directly. By doing so, the average throughput of UEs can be significantly improved in compared with the case where D2D communication is not used (red curve).

We also evaluate the network performance comparing with other metrics when either D2D communication is enabled or

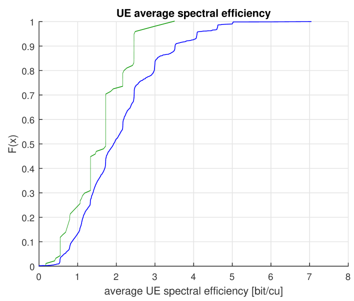

Figure 8: UE Average Spectral Efficiency (with D2D As Green)

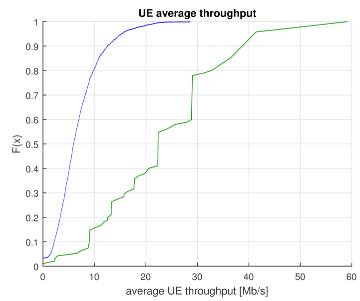

Figure 9: UE Average Throughput (with D2D As Green)

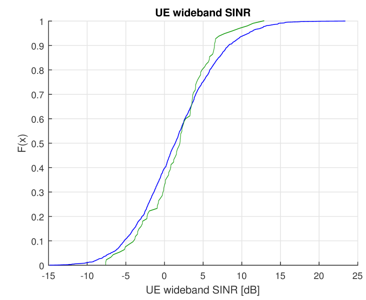

Figure 10: UE Wideband SINR (with D2D As Green)

disabled in the LTE network. Figures 8, 9 and 10 show the CDF of the UE average spectral efficiency, average throughput, and UE wideband SINR, respectively. As we can see, when D2D communication is enabled, the average UE throughput is continuously improved (almost doubled) and this is exactly what we expect, the average UE spectral efficiency is decreased because higher throughput demands higher frequencies that can accommodate lower numbers of bits, and SINR has lower range but still many UEs are in good range of coverage from the base stations.

5. CONCLUSION

In this paper, we investigated Wi-Fi Direct as an outband solution of D2D communication in LTE-based cellular networks. To enable the communication among devices that are nearby each other, provide the ability of offloading traffic transmitted via LTE-based cellular networks, and support communications for IoT applications such as the smart grid, we developed a clustering scheme which could create small Wi-Fi network clusters for nearby devices to remain connected to the LTE-based cellular network. Using real-world data collected from a public database in LTE networks and smart meter information, we demonstrated the effectiveness of our proposed scheme with respect to a comprehensive set of metrics.

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