# WiFi Direct and LTE D2D in Action

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***Abstract*—With the evolution of high-performance multi-radio smartphones, Device-to-Device (D2D) communications became an attractive solution for enhancing the performance of cellular networks. Although D2D communications have been widely studied within past few years, the majority of the literature is confined to new theoretical proposals and did not consider implementation challenges. In fact, the implementation feasibility of D2D communications and its challenges are still a relevant research question. In this paper, we introduce a protocol that focuses on D2D communications using LTE and WiFi Direct technologies. We also show that currently available WiFi Direct features permits to deploy the D2D paradigm on top of the LTE cellular infrastructure, without requiring any fundamental change in LTE protocols.**

## I. INTRODUCTION

The emergence of smartphones as mobile computing devices, running dozens of mobile *apps* accessing the Internet, burdened cellular networks with new types of traffic which are often more resource consuming than traditional voice services. The concept of Device-to-Device (D2D) was introduced to reduce this burden on the cellular infrastructure and offload it to User Equipments (UEs). With D2D, users participating in an infrastructured wireless network can exchange packets directly with each other, without passing through the infrastructure (e.g., without using a common access point or the base station).

The authors of [1] proposed D2D communications as an underlay for cellular networks so that the LTE base station (eNB) can avoid sending the same piece of information multiple times when multiple users request the same content. Wang *et al.* [2] propose a base-station-transparent, user-initiated traffic spreading technique which exploits D2D links between users to improve the file transfer delay. Feng *et al.* in [3] propose a resource allocation method for D2D communications to improve the throughput of D2D links. Fodor *et al.* in [4] discuss the design aspects of D2D communications in cellular network. They specifically discuss the challenges of network-assisted D2D communications and elaborate on some possible solutions to support the D2D paradigm. In our previous works [5], [6], we propose to use WiFi D2D links between cellular users to improve the overall network performance in uplink transmission. Notwithstanding the interest for research in the D2D field, so far, there is no literature that proposes how to practically support the D2D paradigm in real cellular networks, considering the existing wireless protocols and infrastructures.

In this paper, we refer to our previous proposal presented in [6], in which we designed a D2D scheme which exploits the co-existence of LTE and WiFi in smartphones to establish D2D communications among LTE users (see Fig. 1). Our proposed architecture requires LTE mobiles to form WiFi clusters, and the cluster traffic flows through a *cluster head* opportunistically and timely selected. The communication between the cluster head and cluster clients (i.e, all members but the cluster head) is performed over WiFi, e.g., WiFi Direct [7]. However, [6] does not specify the implementation of such proposal in a practical LTE infrastructure [8]. Therefore this paper aims to fill the gap between theoretical proposals and realistic implementation. To achieve this goal, we provide a detailed protocol for the architecture proposed in [6]. The protocol is designed in such a way that modifications to the existing LTE standard operations and WiFi Direct procedures are minimized.

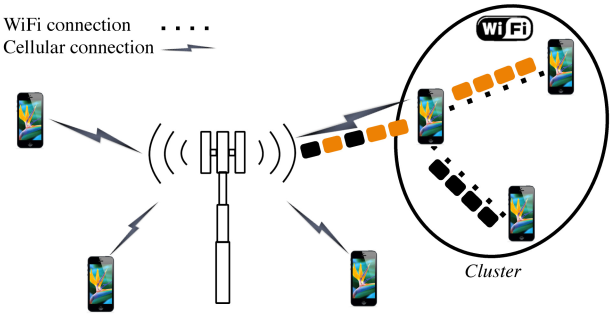

Fig. 1. A D2D architecture for boosting LTE cell performance using infrastructure-less WiFi between mobile devices.

The rest of the paper is organized as follows. Section II gives an overview of the architecture proposed in [6]. Section III explains how to implement a D2D system to assist LTE operations using WiFi Direct. In Section IV, we illustrate some performance figures for the proposed architecture and show that not all previously proposed opportunistic scheduling schemes are suitable for real system implementation. Section V summarizes and concludes the paper.

## II. D2D SYSTEM MODEL

As analyzed in [6], an LTE cellular network can benefit from D2D communications between mobile devices in order to boost energy efficiency, make channel utilization opportunistic, and achieve high fairness while improving network throughput.

The basic idea presented in [6] is that mobile users form groups, namely *clusters*, in which a particular member, namely the *cluster head*, is opportunistically selected based on its cellular channel quality, and it is responsible for relaying the aggregate traffic of the entire cluster. The cluster head changes over time, as it follows a channel opportunistic selection scheme, which guarantees an optimal utilization of LTE resources.

With the proposed scheme, LTE devices form clusters by using their secondary wireless interface, i.e., WiFi, while the cluster head communicates with the base station using the LTE interface. Clusters form only if the WiFi connectivity between cluster members is good (data rates are higher than the LTE load generated in the cluster). Moreover, the results presented in [6] shows that this proposal allows cellular users to enjoy seamless connectivity while spending more time on a secondary, WiFi-based, interface, which is less power consuming than LTE, and switch off their LTE interface for long periods during which the LTE user channel's quality is not the strongest. Therefore, the WiFi Direct paradigm, adopting short-range and low-power transmissions, fulfills the requirements of the architecture proposed in [6].

As concerns scheduling in LTE, results in [6] suggest to implement a Cluster Weighted Round Robin mechanism (CL(WRR)), in which the base station schedules clusters instead of normal users. With CL(WRR), the base station assigns resources according to a classical Weighted Round Robin scheme, in which the weight of a cluster is represented by the number of cluster members. Another interesting cluster-based scheduler proposed in [6] consists in using MaxRate [9] between clusters (CL(MR)), in which, at each subframe, the cluster with the user with the highest channel quality is scheduled. In Section IV we use these two schedulers to comment on the performance of the protocol proposed in the next section, and we compare the performance of cluster-based schedulers to the one of legacy Round Robin (RR) and MaxRate (MR) schedulers.

Before proceeding with the definition of a protocol for WiFi Direct D2D communications in an LTE cell, we now introduce the definitions used in the paper.:

**Cluster:** A group of mobiles which agree to share their LTE connectivity over WiFi interface.
**Cluster members:** All the mobiles which belong to the same cluster.
**Cluster head:** The cluster member with the highest channel quality and acts as the relay to the LTE network. Cluster head changes over time.
**Cluster clients:** Cluster members which are connected to LTE via the cluster head.
**Group Owner (GO):** In WiFi Direct, the group owner is the user who acts like an access point in infrastructure mode. In this paper, we use the terms cluster and group interchangeably. In addition, the terms cluster head and group owner refer to the same entity.
**Group clients:** Users who are connected to the same group owner.
**UE:** A mobile which is capable of both LTE and WiFi communications.
**Social channels:** Channels 1, 6, and 11 of IEEE 802.11 which are used for device discovery purposes.

## III. A D2D PROTOCOL FOR WIFI DIRECT IN LTE CELLS

In this section we show how to implement the scheme proposed in [6] using LTE and WiFi Direct. We show that most of the required operations are implementable over the existing wireless protocols with no changes, while a few clustering operations require minor changes in the management of resources in the LTE protocol stack. Specifically, in what follows, we show how clusters form using WiFi Direct, how cluster access the LTE network and obtain connectivity (establish *bearers*). We also discuss how to handle the mobility of cellular users belonging to clusters and show the protocol stack to be used in the data plan for the relay of traffic through the cluster head. Finally, we discuss how important LTE procedures, e.g., link adaptation, scheduling, security and policing, have to be adapted to support cluster-based D2D communications.

### A. Cluster Formation (WiFi Direct)

In our proposal, the first step is to form a cluster among UEs which are willing to use D2D communications. The cluster formation procedure is mostly coherent with that defined in the WiFi Direct specification [7]. Fig. 2 illustrates this procedure between two UEs. This figure also includes the extra message exchanges which are required for implementation the D2D scheme. We divide the process of group formation into several steps which are described in details below.

**Search and discovery.** The UE that is willing to join a group scans IEEE 802.11 channels for existing groups. If the UE cannot join an existing group, it starts the search process on the social channels. This process consists in sending a *Probe Request* on every social channel and waiting for the response to the *Probe Requests*. Upon reception of a *Probe Response*, the UEs start the 3-way Group Owner (GO) negotiation in which the UEs decide about the group owner and operating channel.

**Group ownership negotiation.** The GO negotiation message contains information such as *P2P Device Info*, *Operational Channel*, *Intent* value (a number from 0 to 15 which shows the UE's willingness to be GO). The negotiating parties inform each other about their *Intent* value and the UE with the highest *Intent* becomes the GO. In our proposal, UEs choose the *Intent* value based on their LTE Channel Quality Indicator (CQI). After the GO negotiation, the communication continues on the operational channel, which the GO selected in the negotiation phase.

**Security setup and IP address allocation:** Next, the GO initiates the WiFi security setup using *Wireless Protected Setup (WPS)*. After the security setup is complete, GO assigns IP address to clients following the DHCP protocol.

**D2D-enabling specific messages.** All the previous steps are standard WiFi Direct procedure. However, the D2D operation proposed in [6] requires two additional steps: $i$) each group client sends an *LTE ID Notification* message, which contains its LTE identity (e.g., SAE-Temporary Mobile Subscriber Identity (S-TMSI)), to the GO; $ii$) the GO broadcasts the *WiFi-LTE ID Association Table* to all group clients.[1] This message includes the LTE and WiFi Direct IDs of all cluster members. This message can also include WiFi Direct group settings such

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[1] In our proposal, two LTE IDs must be shared among cluster members: $i$) the S-TMSI which is used in the registration phase; $ii$) Cell Radio Network Temporary Identifier (C-RNTI) which is allocated to the UE after it is connected to the eNB.

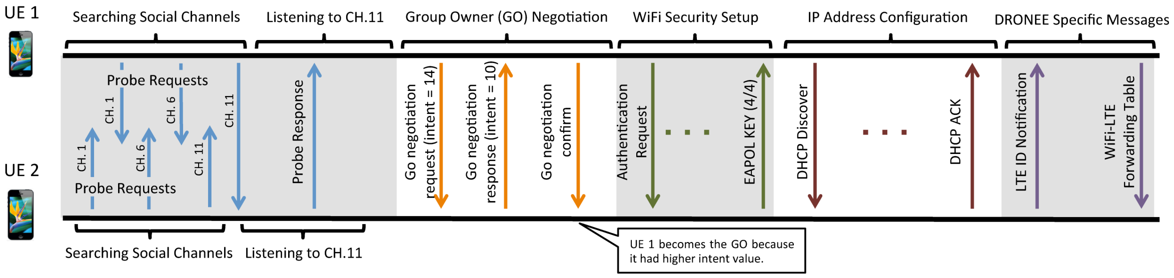

Fig. 2. WiFi Direct group formation procedure.

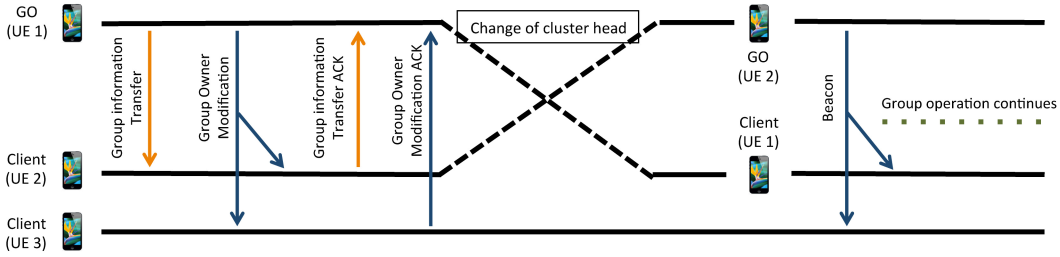

Fig. 3. Group ownership transfer in WiFi Direct. The ownership transfer occurs between UE 1 and UE 2.

as power saving parameters, useful to quickly switch the GO when needed.

**GO transfer.** The group ownership cannot be transferred according to the WiFi Direct specification. However, our proposal requires the GO to change dynamically. A GO transfer occurs when the eNB detects that another cluster member has a better cellular channel quality than the current GO (for details, see *CSI reporting* and *Cluster head selection* procedures in Section III-F). We define two messages in order to support GO transfer in WiFi Direct, as shown in Fig. 3. First, the GO sends the *Group Information Transfer* message to the provisioned GO. This message contains the updated list of members and their power saving related parameters. Second, the GO sends the *GO Modification* broadcast message. Each group client should individually acknowledge this message before the GO transfer is completed.

### B. Cluster Registration in LTE

Once a cluster is formed over WiFi Direct, it should register at the LTE network. Cluster registration procedure is shown in Fig. 4, which reports the required D2D-enabling modifications in red. This procedure consists of two phases: $i$) cluster notification; $ii$) cluster verification.

**Cluster notification.** After cluster formation over WiFi Direct, the cluster head must notify this event to the eNB. The cluster head notifies the eNB by sending the *Cluster RRC Connection Management* message (on Signaling Radio Bearer (SRB) 0) with the *Request Cause* set to connection initiation. Table I shows the contents of this message. The *Dedicated NAS Information* in the message includes the Evolved Packet System (EPS) mobile identities of all cluster members. The eNB responds to the cluster notification with *RRC Connection Setup* message which includes configuration for SRB 1. Next, the cluster head sends the *RRC Connection Setup Complete* to finish the RRC setup. Here, the *Dedicated NAS Information* field is extended to include the EPS mobile identities of all cluster members.

TABLE I. CONTENTS OF CLUSTER RRC CONNECTION MANAGEMENT

| Information Elements | |
|---|---|
| Cluster Identity | To be assigned by eNB |
| Cluster Head Identity | S-TMSI |
| Cluster Clients' Identities<br>(If the cause is initiation, all cluster members should be included. If the cause is Arrival/Departure, only the identity of departing/arriving member(s) is required.) | S-TMSI of Client#1<br>S-TMSI of Client#2<br>⋮ |
| Request Cause | CHOICE |
| | Connection Initiation |
| | Arrival |
| | Departure |
| Dedicated NAS Information (Attach Request) | |

**Cluster verification.** Once the RRC connection is established, the eNB sends a *Security Mode Command* message to each cluster member. Note that the *Security Mode Command* for all clients is received by the cluster head and forwarded to the corresponding client over WiFi. The cluster head also collects the client's responses to the eNB *Security Mode Command* over WiFi and forwards them to the eNB. By forcing the security verification to pass through the cluster head, the eNB ensures that all the cluster clients are already members of the cluster over WiFi. If a cluster head failes to communicate with the eNB, it should transfer the group ownership to one of the cluster clients, see "GO transfer" in Section III-A.

### C. Bearer Establishment

After cluster registration, the cluster head should initiate a cluster bearer establishment procedure. The difference between cluster bearer and UE bearer is in resource provisioning. The allocated resources for a cluster bearer is equivalent to the aggregate of resources allocated to all cluster members. LTE standard defines two types of bearers, namely default and dedicated, to support services with different QoS. The default bearer is established once a UE attaches to the network and it remains until the UE leaves the network. On the other hand, the dedicated bearer is established for services with specific QoS requirement and it remains active for the life

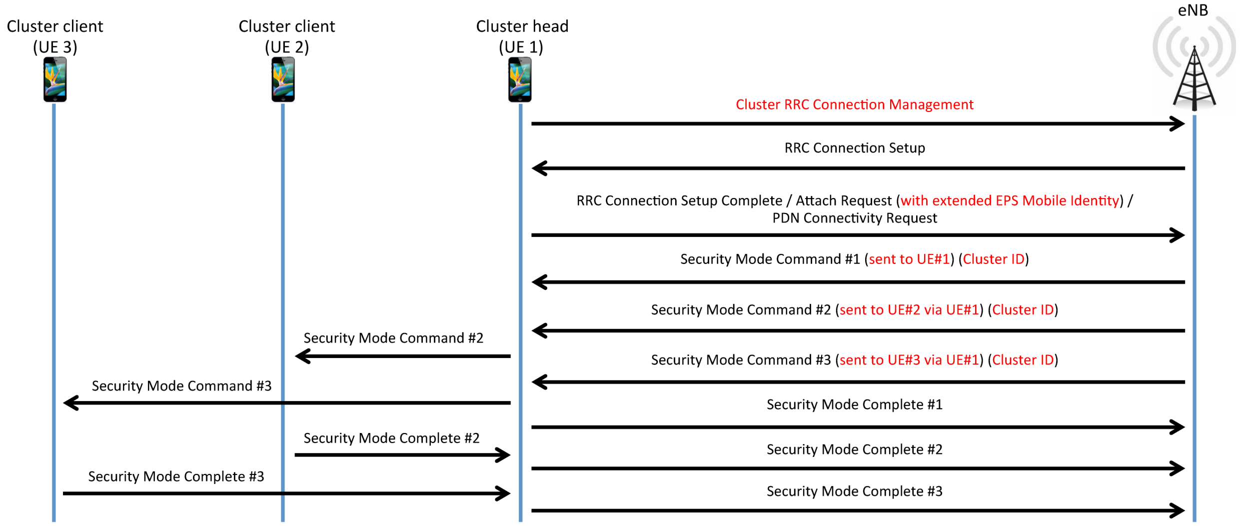

Fig. 4. Cluster registration procedure in LTE.

time of the service. For brevity, we suffice to elaborate on the default bearer establishment. The procedure of dedicated bear establishment requires minor changes in the address field in order to accommodate all cluster members. The procedure for default bearer establishment is depicted in Fig. 5, and it consists of three steps: $i$) bearer request, $ii$) bearer request response, $iii$) bearer request confirmation.

**Bearer request.** After cluster registration is completed, the eNB sends the *Attach Request* to the Mobility Management Entity (MME). The MME determines the International Mobile Subscriber Identity (IMSI) of each cluster member from the information provided in *EPS Mobile Identity* fields of the *Attach Request*. In case the IMSI of a member cannot be identified, the MME explicitly asks for it. Next, the MME sends a *Create Session Request* to the Serving Gateway (S-GW) which contains information such as IMSI of the cluster members and requested Packet Data Network (PDN) connectivity. The S-GW updates its EPS Bearer table and forwards the *Create Session Request* message to the PDN Gateway (P-GW). The P-GW updates its EPS Bearer Context Table and generates a charging profile for every member which does not have one yet.

**Bearer request response.** The P-GW responds to the S-GW request with *Create Session Response* message. In this message the address (assigned by P-GW) and QoS parameters (assigned by Policy and Charging Rules Function (PCRF)[2]) fields are extended to accommodate all cluster members. Naturally, QoS parameter of the cluster bearer is equivalent to the aggregate of members' QoS. Next, the S-GW forwards the *Create Session Response* message to the MME which triggers the *Initial Context Setup Request* sent from the MME to the eNB. This message provides the eNB with settings such as the IP address and the QoS parameters of each cluster members. Again, the IP address and QoS parameters fields of the *Initial Context Setup Request* message is extended to accommodate all cluster members. Note that this reduces the signaling overhead compared to standard LTE operation because the network does not need to send this information to each UE separately. Finally, the eNB extracts the *Attach Accept* message from the *Initial Context Setup Request* and sends it to the cluster head in an *RRC Connection Reconfiguration* message.

**Bearer request confirmation.** The cluster head updates the cluster clients with information received from the eNB. It also sends two messages to the eNB in response to *RRC Connection Reconfiguration* message. An *RRC Connection Reconfiguration Complete* message which is basically an acknowledgment to the *RRC Connection Reconfiguration* and an *Uplink Information Transfer* message in order to complete the NAS attach process. Upon reception of *RRC Connection Reconfiguration Complete*, the eNB sends the *initial context Setup Response* to the MME. This message acknowledges that the E-UTRAN Radio Access Bearer (E-RAB) is successfully setup for the default bearer. It also provides an IP address for communication between the eNB and S-GW for downlink data transfer. After the eNB received the *Uplink Information Transfer* message, it sends the *Attach Complete* message to the MME. The *Attach Complete* and *Active Default EPS Bearer Context Accept* messages trigger the MME to send the *Modify Bearer Request* to S-GW. This message mainly serves as an acknowledgement. Finally, the S-GW completes the process by sending *Modify Bearer Respond* to the MME.

As concerns IP addressing, in LTE, each active UE has at least one default bearer and each default bearer has a unique IP address. Therefore, if a cluster member had bearer(s) before cluster formation, the P-GW keeps the existing IP address(es) associated to the default bearer(s). Once the cluster bearer is activated, the P-GW automatically terminates the old default bearer(s).

### D. Mobility

In our proposal, UEs may join or leave at any time. In this section, we elaborate the procedures for departure/arrival.

**Arrival.** Fig. 6 depicts the procedure followed by a new arrival. In the event of a new arrival, the cluster head sends a *Cluster RRC Connection Management* to the eNB with the *Request Cause* set to *arrival* (see Table I). In this event, differently from cluster registration (see Section III-B), the

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[2] Here, the QoS parameters refer to both per-UE QoS parameter such as Aggregate Maximum Bit Rate (AMBR) and per-bearer QoS parameters such as QoS Class Identifier (QCI), Allocation and Retention Priority (ARP), and Maximum Bit Rate (MBR).

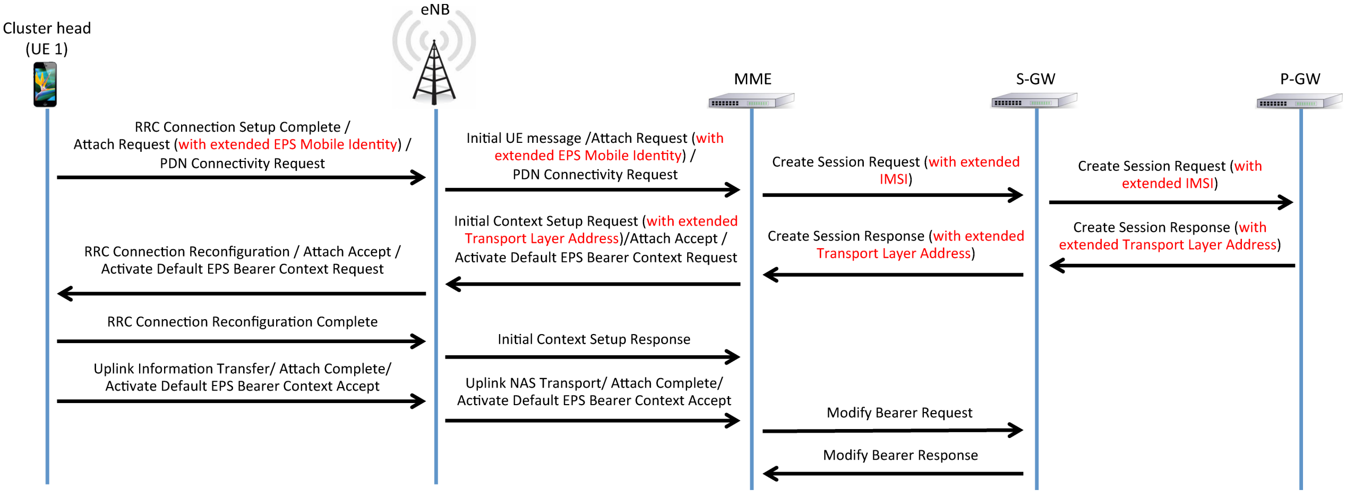

Fig. 5. Signaling required for default cluster bearer establishment.

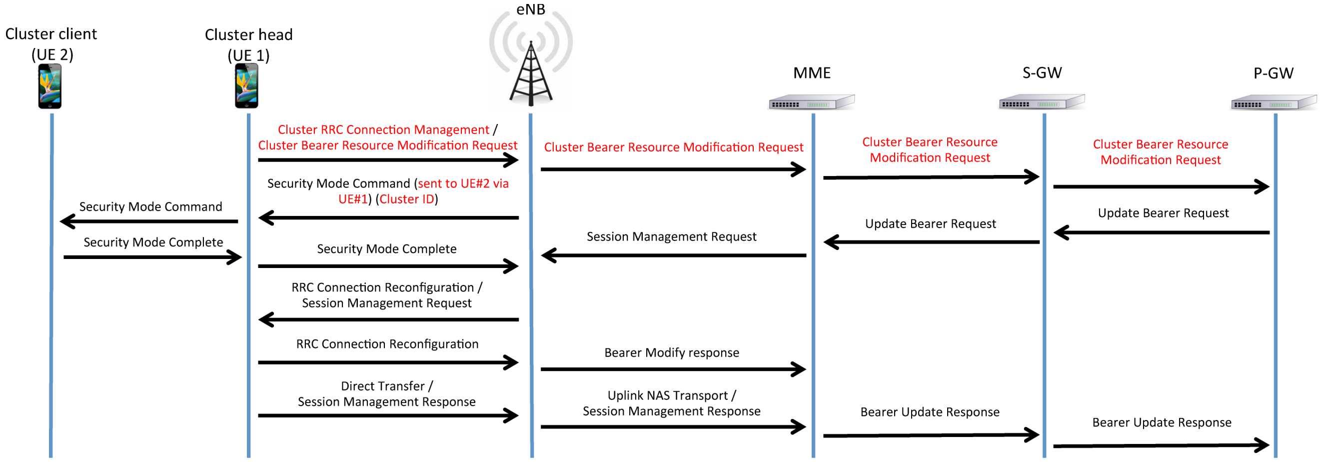

Fig. 6. Signaling messages required for a new arrival.

cluster head only sends the S-TMSI of the new UE. After the eNB receives the notification of new arrival, it sends a *Security Mode Command* to the cluster head to verify the new member. After the verification phase, the eNB sends the *Cluster Bearer Resource Modification Request* message, see Table II, to the MME. The MME replaces the S-TMSI identity in the *Cluster Bearer Resource Modification Request* message with IMSI and forwards the message to the S-GW. The S-GW updates the EPS Bearer Table and sends the *Cluster Bearer Resource Modification Request* message to the P-GW. This initiates the standard LTE bearer modification process as described in [10]. For the sake of brevity, we will not explain the rest of the signaling messages because they follow the standard LTE-defined procedure.

**Departure.** The signaling procedure for a departure is very similar to that of an arrival. The only procedural difference between arrival and departure is that the eNB does not need to send the *Security Mode Command* in case of departure. Moreover, according to WiFi Direct specification, the members should send a de-authentication message to the cluster head before departure. The de-authentication message triggers the cluster head to initiate the departure procedure. Nevertheless, If a UE sends an *RRC Connection Request* message after it joined a cluster, the eNB assumes that the UE does not belong to a cluster anymore.[3] In this case, the eNB initiates the departure procedure without receiving the departure notification message from the cluster head. If a UE is reported as a new arrival of a cluster (i.e., $C_a$) while it is listed as a member of another cluster (i.e., $C_b$), the eNB initiates the departure procedure for $C_a$ and an arrival procedure for $C_b$.

TABLE II. CONTENTS OF CLUSTER BEARER RESOURCE MODIFICATION REQUEST

| Information Elements | |
|---|---|
| Identity of Departing/Arriving Member(s) | S-TMSI(s) |
| Request Cause | CHOICE |
| | Arrival |
| | Departure |

### E. Data Plan Operation

In this section, we show the adaptation of LTE and WiFi Direct data protocol stacks to our proposal. We choose to bridge, at the cluster head, the WiFi Direct MAC and LTE at Packet Data Convergence Protocol (PDCP) layer for three reasons: $i)$ LTE packets are ciphered and integrity-protected

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[3] Our proposal does not permit UEs to have user bearer and cluster bearer simultaneously.

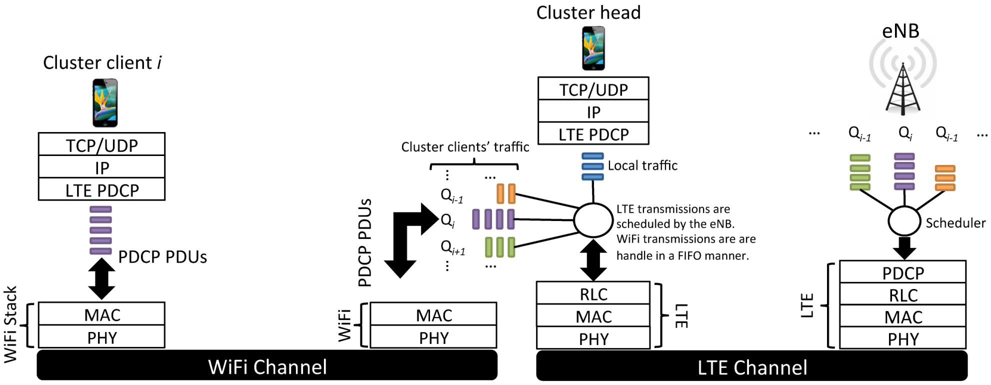


Fig. 7. Data flow between cluster client $i$ and the eNB.

in the PDCP layer using keys which are only known to the client and the eNB. Therefore, other UEs cannot decipher the LTE packets traversing WiFi network; $ii$) the cluster head can further process PDCP Packet Data Unit (PDU)s in RLC layer for concatenation/segmentation according to its LTE physical link quality; $iii$) the WiFi Direct MAC provides a robust and secure transmission service, and natively allows to send frames to be relayed at MAC layer. Fig. 7 illustrates the packet flow through the stack in both uplink and downlink directions which are explained below. Note that the resulting LTE and WiFi Direct data transfer operations are decoupled. Indeed, the cluster head uses the legacy ACK/NACK to secure all the handled LTE traffic, so that ARQ/HARQ operations are managed at the cluster head only, as if the exchanged LTE PDUs were all belonging to the cluster head. Similarly, the normal ACK and retransmission mechanisms are used by the WiFi Direct interface to transfer LTE PDUs in a legacy 802.11 payload.

**Uplink.** As concerns uplink transmission requests, the clients send their *Scheduling Request* (SR) or *Buffer Status Report* (BSR) to the cluster head to be forwarded to the eNB. To do so, they include their requests in 802.11 management frames, using one of the currently unused *subtype* values in the *Frame Control* field of the MAC header [11]. The eNB uses DCI to inform UEs regarding their downlink and uplink resource allocation. Since the cluster head is the only member which is listening to the LTE channel, it receives the DCI and updates the clients with scheduling decision made by the eNB, using an 802.11 management frame with the same subtype value used by UEs to encapsulate SR and BSR messages in the WiFi Direct frame. As concerns data packets, the scheduled cluster clients encapsulate the LTE PDCP PDUs in WiFi frames and send them to the cluster head. A default 802.11 MAC address has to be formally assigned to the eNB, to be used in addition to the sender and receiver MAC addresses as the relay address in the 802.11 frame. In this way, the payload of uplink transmissions carried by WiFi Direct frames are automatically dispatched to the LTE relay queues of the cluster head. The cluster head extracts the PDCP PDUs, processes them through RLC and forwards them to the eNB in the designated slot. The cluster head transmits the packets to the eNB with the client's C-RNTI address in order to simplify identifying the real source of the packets for the eNB. Since LTE data packets are ciphered and integrity protected, there is no security complication.

**Downlink.** The eNB transmits the packets using the client's C-RNTI address but it selects the Modulation and Coding Scheme (MCS) according to the cluster head's channel quality. Since the cluster head is aware of scheduling plan for its clients, it listens to downlink channel to receive the packets belonging to all cluster members. Next, the cluster head encapsulates the PDCP PDUs in regular WiFi data frames that include, a part for the source and destination MAC addresses of cluster head and client, the default MAC address of the eNB. In this way, the cluster head can send the LTE traffic to the clients, and the clients can detect that the payload contains PDCP PDUs from the presence of the eNB MAC address in the WiFi Direct frame.

### F. Adaptation of LTE Procedures

So far we have defined the required messaging to support our proposed architecture in LTE and WiFi Direct platforms. In this section, we elaborate on the adaptation of our proposal to important operations, namely Channel State Information (CSI) reporting, cluster head selection, scheduling, security and policy control and charging.

*1) CSI reporting:* The LTE standard mandates the UEs to send CSI reports to the eNB for scheduling purposes. In our proposal, the cluster head sends the CSI reports of all cluster members to the eNB. This creates some flexibility which does not exist in the standard LTE operations. For example, the cluster clients can report the CSI over all sub-bands to the cluster head over WiFi. Then the cluster head filters these reports and sends the list of top candidates on each sub-band to the eNB. Alternatively, the cluster head reports the $n$ highest CQI to the eNB. The value of $n$ imposes a trade-off between opportunistic gain and spectral efficiency. Note that such a high resolution CQI report would not be possible in normal LTE operations.

In our proposal, the cluster clients are always in *RRC Idle* mode while the cluster head only goes to *RRC Idle* if none of the cluster members have packets to send/receive. Note that being in *RRC Idle* mode does not impose any constraints on CSI reporting because the UEs in *RRC Idle* wake up once in each Discontinuous Reception (DRX) cycle to listen to paging messages and to perform channel measurement. Differently from standard LTE that uses this measurement locally, we propose to send the CSI reports to the cluster head over WiFi.

*2) Cluster head selection:* The eNB selects the cluster head among the cluster members based on the CSI reports that are received from the cluster head. In our proposal, an extra field is added to the Downlink Control Information (DCI) so that the eNB can transmit the C-RNTI of the new cluster head to the current cluster head. This triggers the current cluster head to initiate the group ownership transfer procedure (see Section III-A). The cluster head selection interval is implementation specific and it is constrained by the delay of LTE network and group ownership transfer in WiFi Direct. This interval introduces a trade-off between signaling overhead and opportunistic gain. On one hand the opportunistic gain is maximized when the cluster head selection is performed on a per-frame basis (shortest possible interval). On the other hand, per-frame cluster head selection requires fast transmission and more signaling overhead. Earlier, we defined a cluster head as the cluster member with the highest channel quality. The followings are a few other possible implementations: $a$) the cluster head is the member with the highest battery level; $b$) the cluster head is the member with highest backlog; $c$) if multiple members have the same highest CQI (i.e., there is a tie), the cluster head is the member which served the least as a cluster head until that moment.

*3) Scheduling:* The existing LTE scheduler can be adapted to support our proposal with a minor modification. In LTE, the eNB selects the physical layer parameters based on the CSI of the scheduled UE. However, our proposal requires the eNB to select physical later parameters of a scheduled UE, which belongs to a cluster, according to the CSI of the cluster head. Therefore, the cluster head can decode the packets and forward them to the corresponding clients. Note that the eNB still uses the C-RNTI of the client in the DCI so that the cluster head is aware of its tranceiving schedule in uplink and downlink. This also eliminates the need for an uplink intra-cluster scheduler in the cluster head.

*4) Security:* As mentioned earlier, our proposal does not introduce any new security threats to the existing LTE architecture because the LTE packets are ciphered and integrity protected before forwarding. We also propose to send *Security Mode Command* through the cluster head, so that the cluster head cannot exploit a UE's resource without its presence in the cluster. The only attack occurs when a malicious cluster head that drops packets of its clients. The eNB can detect such behavior by tracking the number of communication failures of each cluster head. If these failures exceed a certain threshold, the eNB concludes that the cluster head is either facing technical difficulties or trying to disrupt the clients' service. Hence, the eNB can simply change the cluster head and avoid selecting that member as a cluster head for a certain period of time.

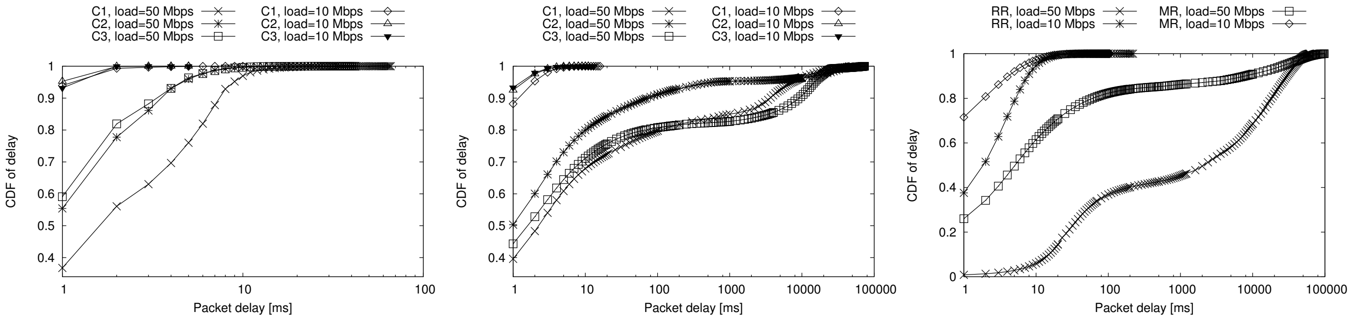
*5) Policy control and charging:* Since the cluster head is in charge of the LTE transmissions for all cluster clients, it is important to make sure that the cluster head is not billed for the clients' traffic. The policy control and charging of LTE is done via Policy and Charging Enforcement Function (PCEF) which charges the UEs based on their IP address. Since each cluster member is given a separate IP address, our proposal does not introduce any problems in billing. It is also important to ensure that members do not utilize each other resources. Since the eNB schedules the members individually, utilizing the other cluster members' resources is not a concern. In case a malicious cluster head transmits its own packets on a slot allocated to another member, the eNB discards the cluster head data because it cannot be deciphered.

## IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our proposed schedulers using our home grown LTE simulator written in Mathematica software. We have shown in [6] that, when the network is saturated, our proposed scheme improves throughput and energy efficiency up to 50% and 30% respectively w.r.t. a classic scheduling scheme such as RR. In addition we showed that the clustering approach significantly improves the fairness. Here, we focus on the non-saturated network case, and evaluate the delay in the LTE cell and the load offered to the WiFi network, which provides us with better insight on the practicality of our scheme. We simulate a cellular system with three clusters C1, C2, and C3 with 6, 8, and 10 members. According to [6], these cluster sizes are practically sufficient to boost network performance to its upper bound. The average SNR of users are selected randomly with a uniform distribution between 7 db to 23 db. The instantaneous channel quality of the uses follows a Rayleigh distribution. All users have homogenous Poisson packet arrivals with the total load of either 10 Mbps or 50 Mbps, depending on the experiment. Note that, we selected the 10 Mbps to show the performance of a lightly loaded system, in which a legacy RR scheduler can suffice, while considering the 50 Mbps case allows us to validate the benefits of our D2D-assisted scheme when the network is close to saturation and legacy schedulers cannot manage efficiently the offered load. In fact, the capacity of the network under cluster-based and legacy MR schedulers is $\sim$ 70 Mbps, as we verified through simulation. The duration of each simulation is 100 seconds and every simulation is repeated for 25 different seeds. The delay results for CL(WRR) and CL(MR) are shown per cluster and the delay results for RR and MR are the averaged over all users.

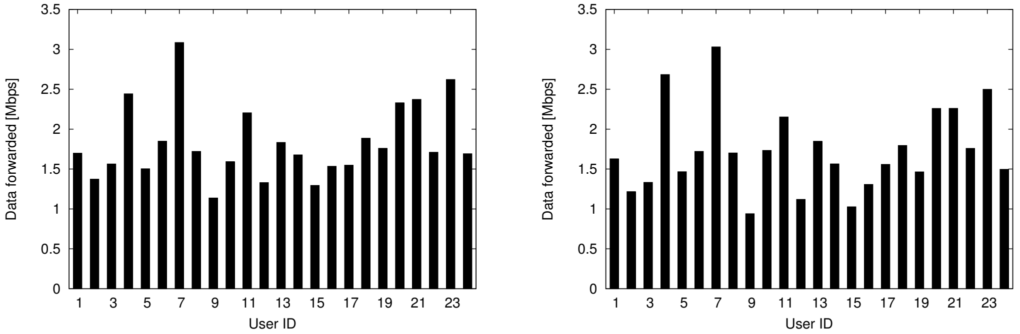
Fig. 8 shows the average delay CDF of different schedulers under low traffic (10 Mbps) and high traffic (50 Mbps) loads. We can observe in Fig. 8 that under low traffic load CL(WRR) and CL(MR) achieve a much lower delay that what achieved under RR and MR, up to 50% lower. Under high traffic load, CL(WRR) outperforms the rest of schedulers by maintaining the delay under 50 ms which is the delay budget for real time services in the LTE. In fact, Table 6.1.7 in [12] specifies that the packet delay budget of the LTE defined QCIs is between 50 ms, for real time services such as gaming, to 300 ms, for elastic services such as web browsing. Under high traffic, CL(MR) does not perform as good as CL(WRR) but it still performs better than RR and MR, which achieve very high delays with high probability. Specifically, from Fig. 8(c) it is clear that RR and MR exceed 300 ms delays with probability 60% and 20%, respectively. The cause of poor delay performance in CL(MR) is the greedy behavior of the scheduler in prioritizing the user with the highest throughput, which leads to maximal spectral efficiency but non-optimal delay and fairness performances [6].

Interestingly, with CL(WRR) we can guarantee delays lower than 10 ms with 99% probability or higher, which leaves at least 40 ms of packet delay budget for WiFi Direct



(a) Delay CDF for CL(WRR). (b) Delay CDF for CL(MR). (c) Delay CDF for RR and MR.

Fig. 8. CDF of delay for cluster schedulers and user schedulers.



(a) WiFi Direct load per cluster member under CL(WRR). (b) WiFi Direct load per cluster member under CL(MR).

Fig. 9. WiFi Direct load due to D2D-assisted cluster-based scheduling.

transmissions. Therefore, CL(WRR) is a suitable scheduler candidate for real implementation.

We can see the the load offered to the WiFi network under CL(WRR) and CL(MR) in Fig. 9. This figure confirms that the WiFi Direct network is not a bottleneck in our proposed architecture. Figs. 9(b) and 9(a) show that the loads offered to C1 (users 1 to 6), C2 (users 7 to 14), and C3 (users 15 to 24) under both schedulers are less than 10 Mbps, 15 Mbps, and 20 Mbps, respectively. The load variation for different users depends on the channel quality. For instance users 4 and 7 relay more traffic because they have higher average SNR w.r.t. the other users. In all cases, the traffic to be handled by each WiFi Direct group is well below typical WiFi capacities.

## V. CONCLUSIONS

In this paper, we have proposed a practical protocol for supporting D2D communications in cellular networks using WiFi Direct and LTE. This protocol, to the best of our knowledge, is the first of its kind. Specifically, we detailed how D2D communications can be supported over LTE network with minor modifications to the standard procedures without any infrastructural changes. Our simulation results confirmed that: $i)$ our proposed D2D architecture performs well in terms of delay and traffic load to be sustained by D2D transmissions, and $ii)$ the CL(WRR) scheduler minimizes LTE packet delays, which leaves room for relaxed WiFi operations at reasonable transmission rates, i.e., at most 25 Mbps.

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