An SDR-based Experimental Study of Outband D2D Communications

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***Abstract*—Device-to-Device communications represent a paradigm shift in cellular networks. Analytical results on D2D performance are very promising, but there is no experimental evidence that validates these results to date. This paper is the first to provide an experimental analysis of outband D2D schemes. Moreover, we design DORE, a complete framework for handling channel opportunities offered by outband D2D relay nodes. DORE consists of resource allocation optimization tools and protocols suitable to integrate QoS-aware opportunistic D2D communications within the architecture of 3GPP *Proximity-based Services*. We implement DORE using an SDR framework to profile cellular network dynamics in presence of opportunistic outband D2D communication schemes. Our experiments reveal that outband D2D communications are suitable for a large variety of delay-sensitive cellular applications, and that DORE enables notable gains even with a few active D2D relay nodes.**

I. Introduction

Device-to-Device (D2D) communications gained rapid traction in academia and industry in recent years. The popularity of D2D is due to its potential for solving a large spectrum of pressing issues in today's cellular networks, e.g., insufficient capacity and lack of solutions for public safety applications. Indeed, a plethora of different studies have sprouted from the D2D research niche [1]–[6], which all agree on the crucial role of D2D in upcoming wireless systems. Analytical and simulation-based results of these studies demonstrate outstanding gains, especially under opportunistic channel utilization. However, D2D schemes are tightly integrated with the cellular infrastructure, which is rare commodity in academia, hence the lack of experimental evaluations.

3GPP is actively studying the feasibility and the architecture of D2D communications to finalize the standardization process for both *inband* and *outband* D2D modes, in which inband D2D uses the cellular spectrum, while outband D2D uses unlicensed spectrum. More in general, the state-of-the-art clearly shows that inband D2D is a well-explored topic [7], [8]. However, its standardization is progressing slowly due to the significant modifications required for accommodating D2D users in the cellular spectrum. In constrast, outband D2D communications do not require significant modification in the resource management of the cellular spectrum, which explains why they are now receiving more attention [1]. The pivotal technological challenge to implement outband D2D schemes consists in the User Equipment (UE)-relay feature, which undergoes an extensive investigation in the 3GPP's study on architectural enhancements to support *Proximity-based Services* (ProSe) [9]. With the above it will be possible to tackle D2D use-cases such as content sharing, offloading, and public safety using the unlicensed spectrum to assist cellular operation.

This paper is the first to build an SDR-based experimental testbed for outband D2D communications. In particular, we leverage the experimental setup for rigorous tests investigating the performance and practicality of channel-opportunistic outband D2D communications under tight QoS constraints.The following list summarizes our contributions: (i) We design D2D Opportunistic Relay with QoS Enforcement (DORE), a channel-opportunistic framework for enhancing network capacity under QoS constraints; (ii) We formulate DORE as a QoS-aware throughput maximization problem to perform relay and mode selection for ProSe-enabled UEs. In this paper, a UE is either in outband D2D mode or legacy cellular mode. Inband D2D is out of our scope; (iii) We design a greedy algorithm for implementing DORE, based on the aforementioned problem formulation for time-stringent operations; (iv) We design a protocol to integrate DORE into the 3GPP ProSe architecture; (vi) We point out a few shortcomings of ProSe and propose new amendments; (v) Using an SDR platform and commercial-off-the-shelf Android devices, we implement the first experimental testbed for DORE and, more in general, for outband D2D and opportunistic outband D2D solutions; (vi) We evaluate outband D2D and DORE with real-time video streaming and non delay-tolerant flows.

Our results indicate that outband D2D is indeed a feasible scheme that is suitable for a large variety of cellular applications. We also show that not only channel quality-based opportunities exist in abundance in a cellular network, but also it is feasible to design simple schemes to leverage such opportunities efficiently.

II. DORE

Despite the unavailability of standardization for D2D communications, the possible D2D architecture designs could be deduced from the ongoing feasibility studies and technical reports that deal with D2D (see in particular [9]–[11]). In

Rohit Gupta was affiliated to National Instruments, Dresden within the course of this work.

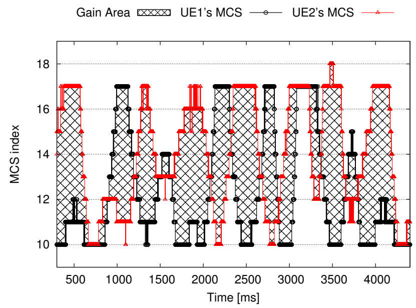


Fig. 1. A snapshot of MCS indices for 2 UEs, and their *Gain Area*.

this section, we design DORE, a framework for *signal-quality based* opportunistic outband D2D relays, as the key-enabler technology for improving wireless users' performance. DORE is based on an optimization problem we formulate for relay/mode selection with delay constraints. Given the NP-Hardness of the optimization problem, we design a greedy algorithm for DORE. Moreover, to evaluate the performance of DORE, we design a practical protocol that leverages and amends the existing 3GPP ProSe framework. In this paper, we assume that UEs are able to communicate using Legacy Cellular mode or Outband D2D mode.

A. System Model

In DORE, UEs establish outband D2D links using WiFi in unlicensed bands, and exploit the channel diversity of cellular networks opportunistically. To this aim, the eNB evaluates the reported Channel Quality Indicators (CQIs) of the D2D UEs and uses the UE with the highest CQI as the relay. Therefore, at each scheduling epoch, a relay node receives its own traffic plus the traffic for other UEs (i.e., D2D receivers) with lower channel qualities. Also, at each scheduling interval, the roles (i.e., relay or receiver) can be switched according to the reported CQI values. Nevertheless, if use of outband D2D link results in violation of QoS constraints, the UEs fall back to cellular mode. Note that a relay node can serve multiple receivers simultaneously.

The described opportunistic outband D2D relay scheme is compatible with any scheduling mechanism employed at the eNB. In particular, in DORE, the eNB scheduler allocates the resource blocks to the UEs connected via D2D in the same manner as for legacy cellular UEs, except that: (i) Modulation and Coding Scheme (MCS) of the D2D receiver is adapted to the MCS of the UE acting as relay, and (ii) the relay receives the traffic of the D2D receiver over cellular interface and forwards it over the D2D link. This source of opportunistic gain is better illustrated in Fig. 1. In the figure, we show a snapshot of the best MCSs usable by UE1 and UE2 over an interval of $\sim 4s$. The potential gain from opportunism is the area enclosed between the two curves (i.e., the *Gain Area* indicated in the figure). Opportunistic outband D2D is clearly beneficial for UEs with low correlation of channel qualities.

B. Problem Formulation

One of the main concerns about outband D2D is maintaining the QoS requirements of the flows. Hence, we formulate an optimization problem for DORE to maximize system throughput by performing relay/mode selection under delay constraints.

Following the proposed design by 3GPP, we assume that throughput and location information of the users are available at the ProSe Server. In addition, the users report the achievable rate and delay of their D2D link to the eNB. The throughput of a user i who receives it's data directly from the eNB can be expressed as $T_{lte}^{(i)} = r_{lte}^{(i)} b_{lte}^{(i)}$, where $r_{lte}^{(i)}$ is the achievable rate over LTE and $b_{lte}^{(i)}$ is the allocated bandwidth. Alternatively, the throughput of a user i that receives its traffic from a relay j is expressed as $T_{d2d}^{(ij)} = \min(r_{lte}^{(j)} b_{lte}^{(i)}, r_{wifi}^{(ij)} b_{wifi}^{(i)})$, where $r_{lte}^{(j)}$ and $r_{wifi}^{(ij)}$ are the achievable rate of relay over LTE and the achievable WiFi rate between the relay j and the receiver i, respectively. $b_{wifi}^{(i)}$ is the available bandwidth to user i over WiFi. Naturally, $T_{d2d}^{(ij)}$ is the minimum between the throughput of the two links (i.e., LTE and WiFi). The over the air delay from the eNB to a user i when j is the relay ($j = 0$ when no relay) is denoted by $d^{(ij)}$. Given these definitions, we can formulate DORE as a throughput maximization problem with delay constraint $d_{th}^{(i)}$ for N users as follows:

$$\begin{cases} \max & \sum_{i \in \mathcal{N} \setminus \{0\}} \sum_{j \in \mathcal{N} \setminus \{i\}} (\alpha_{ij} T_{lte}^{(i)} + \alpha_{ji} T_{d2d}^{(ij)}) \\ \text{s.t.} & \alpha_{ij} \in \{0,1\} \quad \forall i,j \in \{0, \cdots, N\} \\ & \alpha_{ii} = 0 \quad i \neq 0 \\ & \alpha_{00} = 1 \\ & \sum_{i \in \mathcal{N}} \alpha_{ij} = 1 \\ & \sum_{j \in \mathcal{N}} \alpha_{ij} - (N - 1 + 2\delta_{0i})\, \alpha_{0i} \leq 0 \\ & d^{(ij)} \leq d_{th}^{(i)} \end{cases} \tag{1}$$

where α_{ij} is a binary decision variable that determines whether user i transmits to user j or not, and δ_{ij} is 1 for $i = j$ and 0 otherwise. For notational convenience, we mark the eNB as user 0. The first constraint of (1) forces the decision variable to be binary. The second and third constraints avoid a user to transmit to itself with the exception of the eNB. This exception is for notational convenience and it does not have a physical meaning. The forth constraint enforces the users to receive either from the eNB or a relay. The fifth constraint limits the number of receivers of a relay below $N - 1$. Finally, the last constraint keeps the total delay below a threshold.

C. Complexity

Problem (1) is a Knapsack problem that is proven to be NP-Hard [12]. Although the complexity of the brute force algorithm is O(2^{N+1}), the set of feasible solutions is significantly smaller than the original set. The following shows the set of decision variables assuming that m users directly communicate with the eNB (i.e., relay/cellular UE):

$$\begin{array}{c} \\ \\ eNB \\ u_1 \\ \vdots \\ u_m \\ u_{m+1} \\ \vdots \\ u_N \end{array} \begin{array}{c|ccc|ccc} & \multicolumn{3}{c|}{relay/cellular\ UE} & \multicolumn{3}{c}{receiver} \\ eNB & u_1 & \dots & u_m & u_{m+1} & \dots & u_N \\ \hline \alpha_{00} & \alpha_{01} = 1 & \dots & \alpha_{0m} = 1 & \alpha_{0m+1} = 0 & \dots & \alpha_{0N} = 0 \\ \hline \alpha_{10} & \alpha_{11} = 0 & \dots & \alpha_{1m} = 0 & \alpha_{1m+1} =? & \cdots & \alpha_{1N} =? \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_{m0} & \vdots & \vdots & \vdots & \alpha_{mm+1} =? & \cdots & \alpha_{mN} =? \\ \hline \alpha_{m+10} & \vdots & \vdots & \vdots & \alpha_{m+1m+1} = 0 & \dots & \alpha_{m+1N} = 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_{N0} & \alpha_{N1} = 0 & \dots & \alpha_{Nm} = 0 & \alpha_{Nm+1} = 0 & \dots & \alpha_{NN} = 0 \end{array}$$

For the sake of presentation, we sorted the matrix so that the relays and receivers appear in two distinct groups. All elements in the first column, but α_{00}, are zeros because users cannot relay to the eNB. In the first row, all elements are ones but the D2D receivers because they are not suppose to communicate with the eNB directly. Since each user can only receive from one source, columns 1 to m (in red box) are all zeros but the first row elements. Finally, rows $m+1$ until N are all zeros because D2D receivers can not transmit to other users. Now, we can see that, using the constraints defined in the problem, the complexity of the actual problem is reduced to a much smaller set of decision variables that is highlighted in light blue color in the top rightmost corner of the matrix. This reduces the complexity of the brute force to $\mathrm{O}\left(\binom{N}{m}2^{N-m}\right)$. Nevertheless, the complexity is still high for real-time operation. Hence, we design a *greedy* algorithm based on the properties of the formulated problem.

D. A Greedy Algorithm for DORE

The exact solution to Problem (1) is computationally expensive and does not allow for rapid relay and mode selection. We propose a greedy algorithm (`Greedy`) in which we leverage the properties of our problem formulation to reduce the complexity of the problem. In the first part of the algorithm, we compute the potential throughput gain $T_{gain}^{(ij)}$ in different configurations (line 2 to 7). In the second part (lines 8 to 16), we start the relay/mode assignment from the ij pair with the highest $T_{gain}^{(ij)}$ under delay constraint. With this implementation we reduce the complexity to $\mathrm{O}(n^2)$.

Algorithm 1 `Greedy`

Input:
1: $T_{lte}^{(i)}, T_{d2d}^{(ij)}, d^{(ij)} \quad \forall i,j \in \{0,\dots,N\}$.
Output: α_{ij}
2: initialize: $\alpha_{00}=1$, $\alpha_{ij}=0 \quad \forall i,j \in \{1,\dots,N\}$, $T_{gain}^{(ij)}=0$, $\mathcal{D}=\emptyset$.
3: **for** $i \in \mathcal{N}$ **do**
4:     **for** $j \in \mathcal{N} \setminus i$ **do**
5:         $T_{gain}^{(ij)} = T_{d2d}^{(ij)} - T_{lte}^{(i)}$
6:     **end for**
7: **end for**
8: **for** k from 1 to N **do**
9:     find $\mathrm{argmax}_{(ij)}\ T_{gain}^{(ij)}, \quad i \in \mathcal{N} \setminus \mathcal{D}$
10:     **if** $d^{(ij)} \leq d_{th}^{(i)}$ **then**
11:         $\alpha_{ij}=1 \quad \& \quad \alpha_{0i}=1$
12:         $\mathcal{D}=\mathcal{D}\cup\{i\}$
13:     **else**
14:         $T_{gain}^{(ij)}=0$
15:     **end if**
16: **end for**

E. DORE Procedures in a ProSe-Compliant Framework

This subsection is dedicated to elaborate on the integration of DORE in 3GPP ProSe. Fig. 2 illustrates the access network and main ProSe elements (i.e., ProSe Function and ProSe Application Server). The functionalities of these elements are designed to support a large spectrum of use-cases that makes ProSe very receptive to new protocols, including DORE.

1) Registration: UEs register for opportunistic outband D2D at ProSe Function by sending the *Registration Request* message, as shown in Fig. 2. This is necessary for the majority of D2D applications due to the operator-centric nature of D2D communications in cellular networks. In Fig. 2, we assumed that UE1 is already registered. ProSe Function responds to this request with a *Registration Confirmation and Settings* message. This message includes an application ID assigned to the UE for the requested service. The settings specify the periodicity of location updates and discovery beacon, and the discovery channel for the direct discovery method.

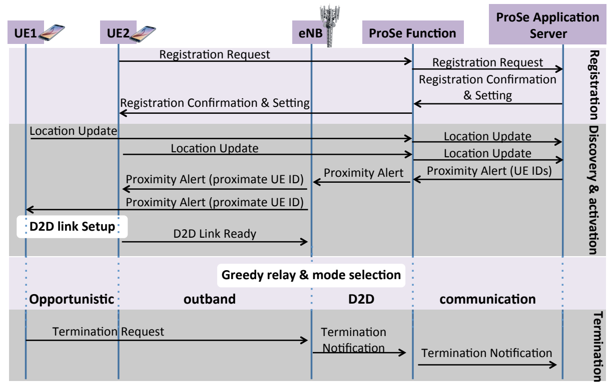


Fig. 2. Schematic protocol overview of DORE.

2) Discovery: Like any other D2D application, UEs can find other UEs in proximity using network-assisted discovery as illustrated in Fig. 2 or independently (i.e., direct discovery). The former is triggered once the network detects that two registered UEs are in D2D range, based on the ProSe defined location reporting [9]. The later resembles the discovery phase in WiFi Direct [13].

3) Activation: Next, the system should establish a path between the eNB and D2D UEs. Since the relay-UE dynamically changes in DORE, path re-configuration should be quick and uninterrupted. The following details this procedure.

Activation

1: ProSe Application Server sends **Proximity Alert** message to the Prose Function. This message contains the application user ID of the D2D UEs in proximity.
2: ProSe Function sends **Proximity Alert** message to the eNB and the UEs. The message to the eNB contains the UE cellular IDs while the message to the UE contains user application IDs to be used for D2D link activation.
3: UEs continue the link activation procedure per WiFi Direct standard.
4: Upon successful establishment of the connection, the UEs send **D2D Link Ready** message to the eNB.

4) Communication: Once the eNB is notified on the D2D link activation, it starts to serve the D2D UEs based on our proposed `Greedy` algorithm for DORE as described below.

Communication

Frame relay

1: The `Greedy` algorithm performs D2D relay/mode selection at the eNB based on the delay and throughput feedback from the D2D UEs.
2: The eNB labels the frames of the D2D UEs so that each UE can differentiate if a received frame is local or it should be relayed.
3: Upon reception of a relay frame, the relay UE processes the packet from physical layer up to Packet Data Convergence Protocol (PDCP) layer.
4: The relay UE encapsulates PDCP Service Data Unit (SDU) in a WiFi frame and forwards it over the D2D link.
5: The D2D receiver decapsulates the relayed frame and processes the PDCP SDU through the rest of the LTE stack.

Periodic updates

6: UEs send regular CQI reports to the eNB for scheduling purposes. The periodicity is determined by the eNB.
7: UEs send the average achievable throughput and delay of the D2D link to the eNB for the Greedy algorithm.

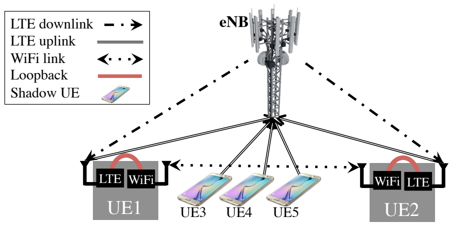


Fig. 3. Architecture of the testbed.

5) Termination: Any D2D UE can send a *Termination Request* message to the eNB so that the eNB terminates opportunistic relaying (see Fig. 2). Next, the eNB will notify the termination of the communication by sending the *Termination Notification* message to the ProSe Function which then forwards this message to the ProSe Application Server.

F. ProSe Amendments

The above description of DORE procedures complies with the 3GPP's ProSe proposed architecture and procedures [9], [10]. However, we opt for a few modifications that improve system performance and security, and reduce the relay overhead.

Label switching instead of IP routing. The current relay solution in 3GPP uses IP routing to relay the traffic between UEs. Such an IP-based approach has a few caveats: (i) The relay has to process LTE frames up to IP layer in order to perform IP routing. This imposes *extra overhead to the relay* UE because the relay is subject to processes such as decompression and deciphering on behalf of the D2D receiver; (ii) Deciphering the relay frames exposes the D2D receiver to *security threats* because the relay UE can potentially monitor the traffic at IP layer; and (iii) The system should handle *IP mobility* because the D2D UEs have two IP addresses (i.e., one cellular link and another for D2D link) and the cellular data can be destined to either interface. In contrast, DORE encapsulates PDCP SDUs in WiFi frames so that the IP handling issues can be disregarded.

D2D link reporting. Current 3GPP standard and academic literature assume that the capacity of WiFi is always higher than the cellular capacity [3], [14]. This is a strong assumption, particularly in dense scenarios as WiFi operates on the unlicensed band that is used by diverse devices/technologies. To avoid overloading the relay UE beyond the capacity of the D2D link, we include an additional message to report average delay and capacity of the D2D link. This is crucial to keep QoS figures under control in the network.

III. Design and Implementation of the Testbed

This section provides a detailed walk-through of our D2D implementation. As illustrated in Fig. 3, our testbed consists of three main components, namely, the eNB, the UEs and the *shadow UEs*. In what follows, we explain each component, its architecture and the interworking among different components.

A. Software and Hardware

We use LabVIEW SDR platform because it allows for quick implementation of CPU intensive Physical layer (PHY) operations with nano-second runtime requirement (e.g., Fast Fourier Transform (FFT), inverse FFT (iFFT), and coding) in a Xilinx FPGA. Moreover, it provides the means for high speed communication with CPU/RF hardware.

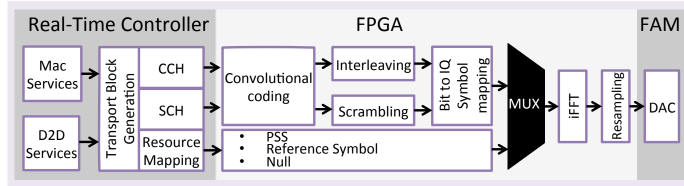


Fig. 4. Architecture of the eNB.

The required hardware for each UE/eNB is emboxed in an NI PXI 1082 chassis that contains: (i) NI PXIe 8135 Real-Time controller operating on an Intel Core-i7-3610QE CPU. This controller hosts LabVIEW Real-Time that executes MAC and PHY control algorithms with micro-second resolution; (ii) NI FlexRIO module with Xilinx Kintex 7/Virtex 5 FPGA, which executes PHY operations; and (iii) NI 5791 FlexRIO Adaptor Module (FAM) that is used as an RF transceiver operating with a 100 MHz bandwidth in the frequency range from 200 MHz to 4.4 GHz. This is used for Digital to Analog Conversion (DAC), Analog to Digital Conversion (ADC).

B. Architecture of eNB

The eNB consists of a Real-Time controller, a Virtex 5 FlexRIO, and a FAM for Over The Air (OTA) LTE transmissions.

Design. Fig. 4 shows the important blocks of the eNB. The Real-Time controller runs MAC layer operations such as scheduling, D2D services, and transport block generation for Control Channel (CCH) and shared channel (SCH). The FPGA executes PHY operations such as interleaving for CCH traffic and scrambling for SCH traffic. Finally, the base-band signal is up-converted in the FAM module and transmitted OTA to the UE. Moreover, we implemented Round Robin (RR) and Proportional Fair (PF) [15] schedulers at the eNB. The former is a benchmark commonly used in the literature. Both schedulers are used in today's cellular networks.

Communication. The current testbed only supports OFDMA in downlink and the uplink transmissions is performed over ethernet. However, in the future we intend to extend this testbed to support OFDMA uplink transmission.

C. Architecture of the UE

The UE consists of a Real-Time controller, a Virtex 5 FlexRIO as OFDMA receiver, a Kintex 7 FlexRio as WiFi transceiver, and two FAMs for OTA communications.

OFDMA receiver. As shown in Fig. 5, the DSP operations are implemented in the FPGA and the Real-Time controller handles the payload processing and MAC layer D2D operations. These operations consist in filtering the relay packets and transmitting them to the receiver over WiFi.

WiFi transceiver. The majority of the WiFi framework [16] is implemented in the FPGA, see Fig. 6. In addition, the transceiver is implemented within the same FPGA. We implemented the D2D state-machine and its corresponding logic

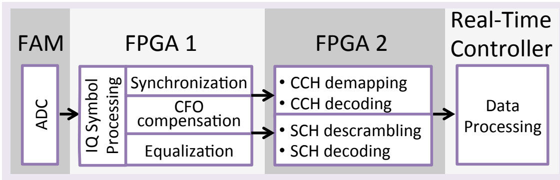


Fig. 5. Architecture of UE's LTE interface.

in the Real-Time controller. The controller is also in charge of feeding data to the FPGA transmission processing chain and reading the decoded data from FPGA processing chain.

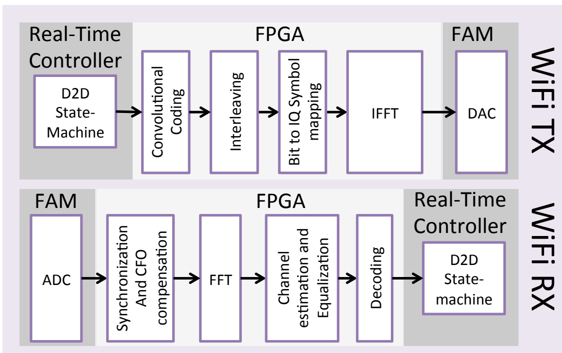


Fig. 6. Architecture of UE's WiFi interface.

Communication. We observe in Fig. 3 that UEs receive downlink transmissions over the OFDMA receiver and send the uplink messages over an ethernet link. The WiFi (i.e., D2D) communication uses an OFDM transceiver.

D. Shadow UEs

These UEs (i.e., UE3, UE4, and UE5 in Fig. 3) are off-the-shelf android smartphones. We include the shadow UEs in our setup to better capture the performance of outband D2D in a real-world scenario. We developed an android application to obtain real-time cellular channel quality on a millisecond basis. The application then transmits the channel quality values to an access point, which is connected to the eNB over an ethernet link. Although the shadows do not receive the actual transmission, the eNB schedules them and transmits their data as if they were real UEs. Since the MCS-SNR mapping is constructed to ensure block error rates below 10^{-4}, we assume that the shadows receive the transmitted blocks with success probability of 0.9999.

Communication. Shadow UEs send CQIs to a wireless access point which is connected to the eNB via ethernet.

E. Synthetic Fading

Due to the limitation in the number of equipments in our disposal, we must run each experiment at a separate time instant. In an ideal case, the system can be connected to high-end multi-channel cellular channel emulators to create the same channel variation in each experiment. Since we do not have such a device, we create a repeatable channel variation situation using refractors. In order to create repeatable channel variation patterns, we mounted the refractors plates on a step motor that is controlled by an Arduino Uno micro-controller. We generate synthetic channel variation by changing the rotation speed of the step-motor.

IV. Experimental Evaluation

In this section, we experimentally evaluate the performance of outband D2D-relay and DORE. We design several experiments to better demonstrate the system behavior in different scenarios. We first present the performance of a simple outband D2D-relay setup. The simple setup is then redesigned to first incorporate channel opportunism and then QoS-awareness. We also examine the impact of non-collaborative UEs (i.e., shadow UEs). The duration of each experiment is 300 seconds, which is sufficiently long to observe the average system's performance. In order to provide the reader with a detailed view of the achieved performance, we show minimum, maximum, 25th and 75th percentiles in addition to the average values. Unless otherwise specified, the rotation speed of the refractor is 5 rpm. Finally, UE2 experiences higher average channel quality than UE1 in all experiments.

A. Selected KPIs

We report several KPIs to examine different aspects of outband D2D-relay and DORE. The KPIs described below are chosen based on their importance for understanding the characteristics of a practical D2D system.

Throughput. Throughput is measured as the number of received bits per second.

Delay. We timestamp each packet at the eNB MAC and measure the delay at three points within the path from the eNB to the D2D receiver. The delay from the eNB MAC to the relay-UE MAC is referred to as *LTE delay*. The delay from the relay's LTE MAC to WiFi MAC is called the *cross-platform delay*. *WiFi delay* is the time from the relay WiFi MAC to the D2D receiver WiFi MAC. The *end-to-end delay* is the sum of all these delays.

CPU load. Since the Real-Time controller executes the D2D related operations, we can provide the extra CPU load due to D2D operations by monitoring the Real-Time module.

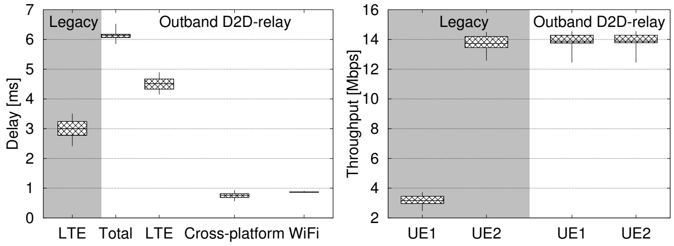
D2D lifetime. We examine our proposed design with slow and fast channel variations. In each case, we measure the time during which a UE acts as relay, which we call *relay lifetime*. This is an important factor in opportunistic D2D because frequent role switching imposes extra load to the system.

Structural Similarity (SSIM). This is an index of similarity between two images and it is known to be a better estimation of human eye perception in comparison to other traditional methods such as peak SNR or mean squared error. We use this metric for QoE measurements in video streaming experiments.

B. Non-opportunistic Outband D2D Relay

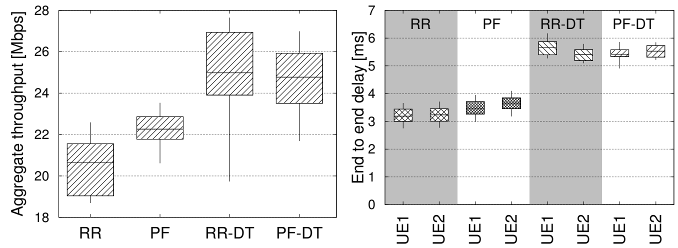
We start with the simplest form of outband D2D-relay scenario with two UEs. Despite the simplicity of this experiment, it provides answers regarding the delay overhead due to multi-hop communication and achievable throughput gain.

Fig. 7(a) compares a *Legacy* scheme (in which both UEs receive traffic only from the eNB) with an *Outband D2D-relay*, in which UE1 acts as relay for UE2. We observe that outband



(a) Delay at different parts of the path. (b) Per-UE throughput.

Fig. 7. Outband UE-Relay: UE1 relays the traffic from the eNB to UE2



(a) Aggregate throughput. (b) Delay

Fig. 8. DORE: the relay UE is chosen according to reported CQI values.

D2D increases the average end-to-end delay (i.e., Total in the figure) by 3.3 ms as compared to the Legacy cellular system. Looking at different delay components of outband D2D-relay, we can see that cross-platform delay and WiFi delay are the major contributors to the delay overhead. It is important to note that extra frame processing results in higher LTE delays in outband relay mode. While commonly ignored in the literature, this illustrates that relaying large volumes of traffic comes at a cost. According to the observation from the delay profile, outband relay could be potentially suitable for a large variety of non-mission critical applications. Indeed, outband relay with a total delay of 6.3 ms meets the 3GPP suggested delay budget of 70 ms [17]. The motive for opportunistic D2D-relay is vividly depicted in Fig. 7(b). The figure shows that UE2 suffers from low channel quality while UE1 experiences a good channel condition. After outband D2D activation, UE2's throughput increases significantly because it receives its traffic through a high channel quality relay.

C. DORE with Delay-tolerant Traffic

Now, we evaluate the performance of opportunistic outband D2D using RR and PF scheduling algorithms. We test DORE with delay-tolerant traffic (i.e., no delay threshold in Algorithm I) to evaluate the potential throughput gain for such use-cases. In the figures, we label the legacy schemes as RR and PF. When used for DORE with delay-tolerant traffic, they are labeled as RR-DT and PF-DT.

Fig. 8(a) shows the achievable aggregate throughput of RR-DT and PF-DT is 21% and 11.2% higher than RR and PF, respectively. As mentioned in Section II, opportunistic outband D2D leverages the channel diversity between the D2D users. Since PF harvests part of this opportunism due to its opportunistic nature, the resulting gain reduces by 9.8% in comparison to RR. Nevertheless, the gain remains relevant for a two-user scenario where there are limited opportunities. We show later in this section that the opportunistic gain increases with the user population. Delay comparison in Fig. 8(b) demonstrates DORE causes higher delays. The additional delay stems from WiFi and cross-platform transmission and LTE frame processing.

D. Impact of Fading Speed

This experiment is designed to show the dynamics of DORE under different fading scenarios. In particular, the change of role in the D2D connection (i.e., a UE can be a relay or a D2D receiver). We refer to the period in which a D2D UE acts as relay as the *lifetime*. In this experiment, we shed light on the frequency of these changes and their impact on the system.

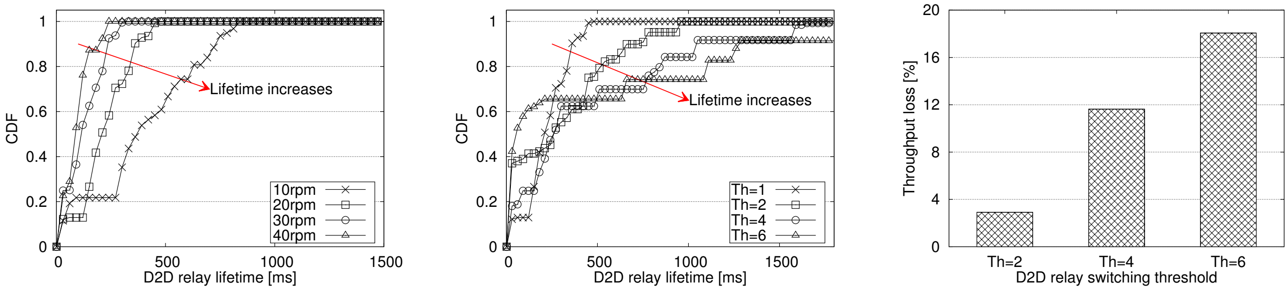
Fig. 9(a) shows the CDF of the lifetime of UEs when the refractor surface spins at 10, 20, 30, and 40 rpm. At these rotation speeds, the MCS of a UE remains the same for 18.86 ms, 15.38 ms, 13.51 ms, and 10.82 ms, on average. We can see that the duration of the lifetimes increases as the fading speed reduces. The results also show that regardless of fading speed, the lifetime is shorter than 250 ms more than 50% of the time. This emphasizes on the fact that *any implementation of opportunistic outband D2D must be capable of handling the relay dynamics on a millisecond timescale*.

In our implementation of DORE, a switch of D2D roles occurs as soon as the achievable MCS of the D2D receiver becomes higher than the one of the relay UE. In other words, the MCS difference threshold to switch roles is one MCS index. Nevertheless, considering the resulting short lifetimes depicted in Fig. 9(a), we have decided to introduce and test hysteresis in the switching to reduce frequent switching. Introducing higher switching threshold can avoid role changes due to small MCS variations that do not vary much in terms of bit efficiency. Thus, we increase the MCS difference that triggers the role switching. Fig. 9(b) shows that larger thresholds (Th in the figure) increase lifetimes, as expected. However, this increment comes at the cost of reduced throughput. Indeed, Fig. 9(c) illustrates that the throughput reduces up to 18% when the switching threshold is 6 MCS levels. Our results indicate that small switching thresholds increase D2D lifetime with limited throughput penalty. Therefore, it is not strictly necessary to reconfigure D2D links upon any MCS change, which reduces the complexity of the implementation.

E. DORE in Presence of Shadows and Delay-tolerant Traffic

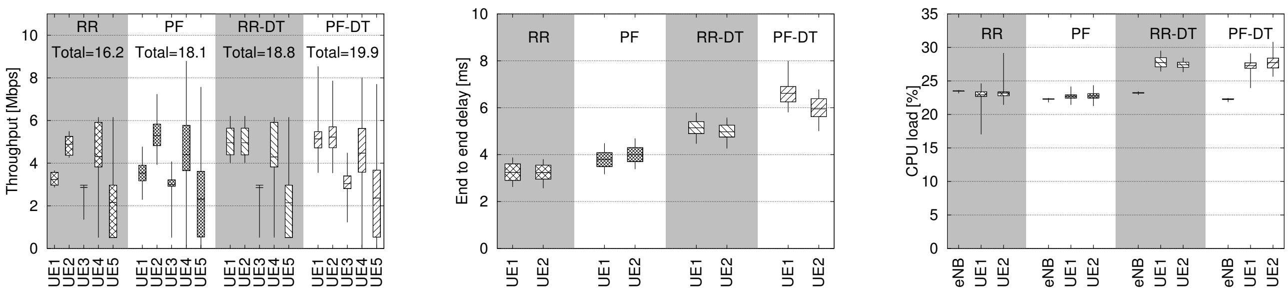
Here, we emulate the presence of additional legacy UEs using the shadow UEs introduced in Section III-D. The shadows do not collaborate in DORE but they help us to test DORE in presence of non-collaborative UEs. The shadows send real-time CQI reports to the eNB, and the eNB schedules traffic for them, although they cannot decode such traffic.

Per-UE throughput results are presented in Fig. 10(a). We can see that UE1 achieves a 53.2% throughput gain with DORE (i.e., RR-DT and PF-DT) while UE2 only achieves a mere 1.4% throughput gain. UE2 achieves lower gain due to its higher average channel quality. We also reported the aggregate throughput of each scheme in Fig. 10(a), marked as *Total*.



(a) Impact of refractor speeds on D2D lifetime. (b) Impact of threshold on D2D lifetime. (c) Impact of switching thresholds.

Fig. 9. Impact of fading speed on the lifetime of D2D UEs.



(a) Per-UE throughput. (b) End to end delay for D2D UEs. (c) CPU load.

Fig. 10. System KPIs in an experiment with two D2D UEs and three shadow users.

DORE results in 10.2% and 9% throughput gain compared to RR and PF. The throughput gains are lower than those achieved in the previous scenario ($\sim 20\%$). This is because in a scenario with 5 UEs, the relay UE receives only a fraction of the total available bandwidth (i.e., $2/5$ of the resources can be relayed if RR is used). As a result, the opportunistic scheme can only optimize that portion of the cellular resources.

Fig. 10(b) depicts the end-to-end delay. The delay behavior of the UEs is very similar to the delay behaviors observed in Fig. 7(a). Both UEs experience additional delay under RR-DT and PF-DT w.r.t. RR and PF because of the aforementioned cross-platform and WiFi delays. UE1 has a higher delay than UE2 because it has lower channel quality than UE2 and it acts as the D2D receiver most of the time.

Fig. 10(c) compares the CPU load of the eNB and the UEs. The overhead on the eNB is negligible. The two D2D-enabled UEs experience 4.42% and 4.45% higher CPU load due to outband D2D operations in WiFi and LTE interfaces. Note that running the WiFi code in the idle mode on the Real-Time controller increases the total CPU load by about 3%. Hence, the overhead due to outband D2D is marginal.

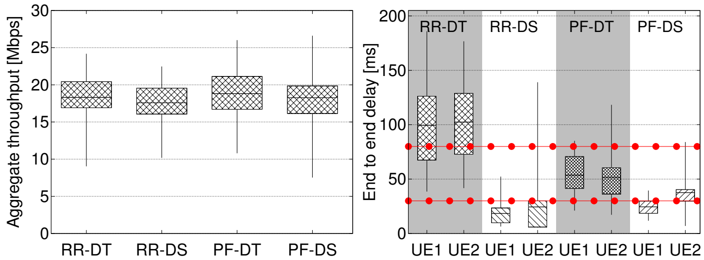
F. DORE in Presence of Shadows and Delay-sensitive Traffic

In this experiment, UE1 and UE2 host a real-time gaming application and a VOIP call with 30 ms and 80 ms OTA delay budget, respectively. To highlight the impact of DORE's QoS-awareness, we also show the performance figures when the delay thresholds are set to infinity (i.e., DORE ignores the delay constraints). In this scenario, we stressed the WiFi channel (i.e., D2D link) by introducing extra non-D2D traffic to the network so that the WiFi channel operates near to the congestion point. Therefore, small changes in the instantaneous channel quality provoke non-negligible size queues.

Fig. 11(a) shows the aggregate throughput of DORE with RR and PF but without QoS constraints (RR-DT and PF-DT in the figure) and with tight constraints (RR-DS and PF-DS). Both RR-DS and PF-DS achieve slightly lower throughput (3%) w.r.t RR-DT and PF-DT because the QoS-awareness of DORE prevents opportunistic relay when delay constraints are violated. However, the 3% throughput loss is a small price to pay to maintain the QoS requirements of the time-sensitive applications. Indeed, we observe in Fig. 11(b) that DORE can successfully cap the average delay below 30 ms and 80 ms. The effectiveness of DORE is especially seen when it reduces the packet delay of the voice traffic from 100 ms to 23 ms and 30 ms. Since DORE delay control mechanism relies on UE feedbacks, it cannot avoid the delay caused by dramatic channel variations. As a result, the maximum delay under RR-DS and PF-DS can be higher than the delay thresholds.

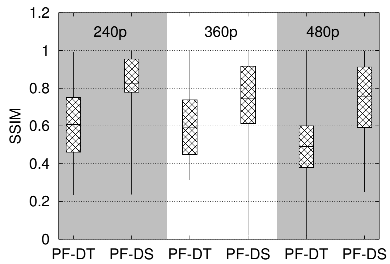
G. Quality of Experience (QoE) with DORE

Good QoS does not necessarily corresponds to good QoE. Thus, we design a video streaming scenario using VLC to measure the QoE in terms of SSIM. We use *AviSynth* to measure SSIM . Both PF and RR demonstrated similar trend hence we only show the result for PF, for brevity. Again, we show in Fig. 12(a) the SSIM of the received video with 30 ms delay constraint (i.e., PF-DS) and with an infinite one (i.e., PF-DT). We repeat the experiment for three different videos with 240p, 360p, and 480p resolutions. The results indicate that the QoS awareness of DORE results in up to 26% SSIM improvement. The SSIM values degrade with higher resolution videos because they are more sensitive to channel impairments. We also demonstrate a snapshot of the received video for 240p and 360p resolutions, in Fig. 12(b). As expected, tight QoS constraints result in better image quality.



(a) Aggregate throughput. (b) End to end delay.

Fig. 11. Impact of QoS-awareness of DORE on system performance.



(a) SSIM between streamed videos.

(b) Snapshots of streamed video at the receiver.

Fig. 12. QoE performance of DORE.

H. Opportunistic Relay within Large Relay Groups

In the previous experiments, only two UEs were allowed to collaborate in DORE. Our observation in Fig. 10(a) showed that the impact of opportunistic outband relay with only two users is limited. Since one-to-many communication is also present in 3GPP ProSe services, we can increase the size of the outband D2D group in order to achieve higher throughput. This experiment is designed to illustrate the impact of larger D2D UEs groups. Here, all UEs report their CQIs to the eNB and we only measure the throughput at the LTE because the shadows are commercial smartphone, which are unable to decode the messages of our experimental eNB. Fig. 13 shows the aggregate system throughput. Our results confirm that by enlarging the outband D2D group from 2 to 5 UEs, the network throughput increases up to 71.8%. The result is critical to confirm the potentials of opportunistic D2D schemes. Indeed, we are the first to assess the opportunistic gain with multiple UEs relaying traffic among each other with a real implementation of an eNB scheduler and real-time CQI acquisition from multiple UEs. The reported results are obtained under PF scheduling. The achievable gains are even higher with RR, as shown in prior subsections.

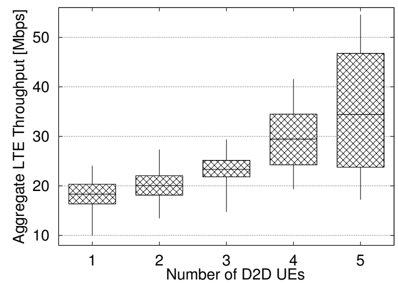


Fig. 13. Aggregate throughput versus the number of UEs in the same opportunistic outband D2D group.

V. Discussion

This work provides in-depth intuitions to understand the practicality of integrating outband D2D communications in cellular networks. This section is dedicated to discuss the feasibility of such integration and to enlighten some key requirements for developing an experimental setup as well as for designing possible use-cases.

Feasibility. The SDR-based implementation of DORE is the proof-of-concept for the feasibility of outband D2D schemes with more complex and dynamic scenarios than non-opportunistic and QoS-unaware UE to UE communications.

Implementation. There are several challenging issues to solve for SDR implementation of a D2D system. Here, we point out the most critical ones. The relay UE experiences high computational overhead due to LTE frame processing. Hence, we propose label switching at LTE PDCP layer instead of IP routing which is the current solution in 3GPP. As explained in Section II-F, the byproduct of this design choice is the elimination of relay-related security concerns. During the course of DORE implementation, we realized that D2D UEs switch role with high frequency (in order of milliseconds). Thus, we place DORE at the eNB instead of ProSe Function/Server to meet timing constraints and to avoid the additional overhead on the backhaul links.

Choice of platform. To date, there are a few SDR platforms with *'simultaneous'* LTE and WiFi capability, namely, Open Air Interface, and LabVIEW. We choose LabVIEW for its modular and graphical programming structure that allows for quick real-time and FPGA code development without stepping into complex low-level programming languages.

Capacity. DORE is key for boosting network capacity in one-to-many relay scenarios. This result is very promising and it may suggest to increase the size of the relay groups as much as possible. However, in virtue of our observations on the extra load due to relay operations, it is plausible to suggest that each relay group should not include more than a handful of users, which is enough to enhance the network capacity by 70%.

QoS. QoS provisioning is a concern in outband D2D due to the use of unlicensed spectrum. As a result, we designed DORE and the surrounding protocol with necessary feedback and handlers to enable QoS monitoring in our testbed. The experiments confirmed that DORE achieves the QoS requirements using a simple monitoring and feedback scheme.

Use-cases. Our experimental evaluation showed that (opportunistic) outband D2D schemes have low latency and ameliorate the throughput substantially. Hence, these schemes suit a large variety of applications including voice calls, video streaming, real-time gaming, and content sharing.

VI. Related Work

The literature on outband D2D both evaluates the potential performance gain using analysis/simulations and studies the feasibility of implementing outband D2D in today's cellular networks. We review the body of work in both groups.

The authors of [3]–[5] study the potential of outband D2D relay. Asadi and Mancuso [3] claim that the combination of opportunistic scheduling and outband D2D achieves 50% capacity gains in comparison to legacy cellular transmissions. Bao *el al.* [4] propose the so called Dataspotting approach that leverages outband D2D communications for content distribution in dense networks. Their proposal consists in using geo-location information of the content and its demand to offload part of the network load over the D2D links. Golrezaei *et al.* [5] propose to use outband D2D and content caching techniques to improve video transmission in cellular networks by one or two orders of magnitude.

In [1], [2], [14], the authors investigate the necessary modifications to integrate LTE and WiFi to implement outband D2D. Andreev *et al.* [1] compare outband and inband D2D in terms of implementation complexity and their standardization progress. The authors conclude that the outband D2D has a higher implementation opportunity because inband D2D requires significant change in the existing standard. In [2] and [14], the authors show that outband D2D can be implemented with minor modifications to the signaling procedure of LTE and group formation of WiFi Direct. In essence, these works point out that D2D is not a far-fetched concept anymore. Moreover, their studies reveal that outband D2D is a viable option for the first commercial implementation of D2D due to its simplicity in comparison to inband D2D.

All the aforementioned works provide numerous analyses that aid towards the understanding of performance gains as well as the potential implications of D2D communications. Nevertheless, neither evaluation in testbed nor real-world implementation without *any simplifying assumptions* has been investigated for outband D2D systems, in contrast to our work.

VII. Conclusions

We prototyped the first SDR platform for outband D2D communications. We leveraged Xilinx FPGAs and the NI Real-Time OS to develop realistic experiments with LTE-like millisecond CQI reporting, scheduling, and high-speed LTE-WiFi interaction. Our experimental evaluation using several QoS and QoE metrics confirmed the feasibility and potentials of opportunistic outband D2D communications. In particular, we designed DORE which is a 3GPP ProSe-compliant and QoS-aware opportunistic outband D2D framework. The results revealed that experimental performance figures are lower than the reported values in the prior analytical studies, although still notable (up to 20% with just two users). Nevertheless, high throughput gains are achievable if the number of participating UEs in opportunistic outband D2D increases (up to 71% with five users). Finally, we are in the process of providing public access to our D2D SDR implementation so that the research community can benefit from deeper study of such a system.

VIII. Acknowledgements

The authors would like to thank Russell Ford, Amal Ekbal, Rene Nuessgen, Vincent Kotzsch, Robert Daniels, Bjoern Bachmann, and Andreas Kruppe for their support in LabVIEW FPGA code development. The work has been partially supported by the Madrid Regional Government through the TIGRE5-CM program (S2013/ICE-2919). This work was supported by the European Commission in the framework of the H2020-ICT-2014-2 project Flex5Gware (Grant agreement no. 671563). This research was supported in part by the Spanish "Ministerio de Economía y Competitividad" under grant TEC2014-55713-R.

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