Multi-frame Transfer for Data Dissemination in LTE Device-to-Device Proximity Discovery

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ABSTRACT

It starts to be widely recognized the growing and central relevance of Device-to-Device (D2D) interactions for future 5G networking and applications, also to stimulate opportunistic collaborations and efficient resource usage based on proximity. A crucial building block to enable such D2D collaboration is proximity discovery, hopefully with so limited network/energy overhead to have the opportunity to be "always-on". This paper proposes an original and efficient multi-frame transport protocol for disseminating data of any length over real industrial D2D solutions. In particular, even if of general applicability, we have originally implemented our protocol on top of the new LTE Direct proximity discovery, which has very strong limitations in the transmittable data for single discovery period. The paper not only describes our development experience with the brand new LTE Direct Qualcomm implementation, but also reports experimental results with the LTE Direct simulator included in the Qualcomm LTE Direct Trial SDK, which are relevant to tune our protocol and to robustly assess its validity.

CCS CONCEPTS

• **Computer systems organization** → **Architectures** → **Distributed Architectures** → n-tier *architectures*; • **Networks** → **Network types** → Cyber-physical networks → Sensor networks

KEYWORDS

Device-to-device Communications; Data Dissemination; Proximity; Discovery; LTE Direct.

1 INTRODUCTION

Device-to-Device (D2D) communications are expected to play a very relevant role in future smartphone generations and in several Internet-of-Things (IoT) application domains, also thanks to the associated opportunities of increasing spatial reuse of spectrum resources and of enabling low latency communication links [1-4]. The D2D paradigm has two fundamental building blocks: i) proximity discovery and ii) direct communication between proximate devices. While the latter one has already received considerable attention by research activities in the very last years, the former has only recently stimulated the first related and significant research efforts, in both industries and academia, in conjunction with the growing interest of its D2D-enabled IoT applications [5-11].

One of the main recognized challenges for the success of D2D proximity discovery is its ability to maintain the discovery functionality "always-on" and at the same time to keep its energy consumption at the lowest level. To this purpose, primary efforts are directed towards minimizing i) the power used in D2D data transmission/reception, and ii) the duration of the D2D active transmission/reception period. For instance, reducing transmission/reception power is often obtained by decreasing the number of channels used for D2D communication. In addition, reducing the active transmission/reception period is often pursued via the synchronization of advertise/scan periods between participating devices.

All the above requirements tend to lead, in D2D proximity discovery specifications for all major wireless connectivity technologies, as better detailed in Section 2, towards a strong limitation in the amount of data that can be sent/received at most in a single discovery period. This is sometimes reasonable and not too limiting for communications in some kind of Machine-to-Machine (M2M) applications, e.g., where a few predefined instructions/data can be expressed using only a very limited number of codification bytes and where the "polling" periods can be very frequent. However, this represents a too strong and limiting constraint when the

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opportunity of proximity discovery could be considered as a starting basis for:

- disseminating human-readable data in target proximity localities via geo-casting, e.g., for traffic monitoring/alert information to drivers;
- distributing larger amount of M2M data at less regular and less frequent time intervals, e.g., because of aggregating/batching actions over IoT gateways in order to improve network/energy efficiency;
- disseminating discovery data about extensive lists of available services in highly scalable deployment environments where large numbers of devices (and their offered facilities) may be present, in particular in dense urban environments.

Given the above impactful opportunities and the many application domains that can benefit from D2D proximity discovery-based data dissemination, we have decided to originally work on a simple but efficient protocol that allows the exchange of (theoretically) unlimited amount of data over any standard D2D proximity discovery solutions available in current wireless connectivity technologies (which are starting to support proximity discovery). Our original protocol splits data to be disseminated into chunks that, by using a dedicated header, can be transmitted independently the one from the other; the protocol is conceived to work in a relatively high-mobility scenario where the probability of losing some chunks is not negligible, also due to the intrinsic low-level characteristics of proximity discovery in all current wireless connectivity options.

In addition to the proposal of this multi-frame transfer protocol per se, which has its primary technical novelty in being suitable for D2D proximity discovery integration, we claim that this paper provides a significant contribution for the community of researchers in the field because it reports the experience and lessons learnt from the design/implementation of our protocol prototype on top of the brand new LTE Direct proximity discovery by Qualcomm. To the best of our knowledge, this is the first paper presenting an implementation (and related simulation work) of a multi-frame transfer protocol over LTE Direct, which is widespreadly considered a promising and potentially impactful technology advancement step if compared to "traditional" LTE, definitely of growing industrial interest for the years to come.

The remainder of the paper is structured as follows. Section 2 overviews the primary characteristics of D2D proximity discovery over the most relevant connectivity technologies where it starts to be standardly supported, i.e., Bluetooth Low Energy, Wi-Fi Aware, and LTE Direct; then, it focuses on the brand new LTE Direct specification on which our prototype works. Section 3 describes our multi-frame transfer protocol for high-mobility scenarios, along with its implementation over LTE Direct. Validation and assessment tests over the novel Qualcomm LTE Direct simulator, as well as conclusive remarks and directions of ongoing research work, end the paper.

2 TECHNOLOGIES AND PROTOCOLS FOR D2D DISCOVERY

For the sake of self-containment and for enabling the full understanding of the original proposal that follows, this section rapidly overviews the state-of-the-art about D2D proximity discovery technologies, by considering all the primary solutions of industrial interest nowadays, i.e., Bluetooth Low Energy (BLE), Wi-Fi Aware, and LTE Direct [12-23]. BLE, also indicated as Bluetooth Smart, is the "low power" and IoT-oriented version of Bluetooth, part of the Bluetooth 4.0 specification. Its power efficiency, mainly obtained principally via reduction of communication channels, well fits the energy requirements of devices that must run for long periods on limited power sources (e.g., coin cell batteries). Wi-Fi Aware, instead, is the new protocol for D2D proximity discovery proposed by the Wi-Fi Alliance, based on the concept of Neighbor Awareness Networking [15]. Wi-Fi Aware allows the always-on discovery functionality with a limited power consumption thanks to its low-duty-cycle Medium Access Control (MAC) and adaptive clustering. The low-duty-cycle MAC exploits an original mechanism to establish a common heartbeat for lightweight communication synchronization. LTE Direct, i.e., the evolution of the FlashLinQ project [3], is the D2D solution proposed by Qualcomm and standardized in the 3GPP Specification (Release 12) under the name ProSe (Proximity Services) [16]. Currently, only BLE is ready to be used in real deployment environments, while LTE Direct is still under development and Wi-Fi Aware is only a specification (not yet implemented), thus demonstrating the freshness of the proposals and the ongoing nature of the associated research and development activities.

2.1 LTE Direct

LTE Direct is an under-development technology for D2D communication by Qualcomm, very promising for D2D proximity discovery because it addresses internally all the related relevant issues, in particular security (authentication) and power consumption (timing). It utilizes licensed LTE spectrum for proximal discovery of devices/services. LTE Direct works seamlessly in collaboration with the regular LTE net-work: only a little amount of bandwidth (under 1%, exact quota depending on the implementation) is periodically assigned to LTE Direct for discovery actions (see the resource allocation example in Fig. 1). The "companion" LTE network is also used for the management of timing, resource allocation, and identification (Fig. 2). In fact, timing is a fundamental feature of LTE Direct, which allows reducing the active time of discovery: Qualcomm states that a device using LTE Direct can discover thousands of devices in approximately 75ms; to compare with existing competitor technologies, BLE devices can only discover hundreds of devices remaining active more than 1s, even with non-negligible battery consumption in such a long activity period [18].

In addition to regular LTE security mechanisms, LTE-Direct has some unique security-related features, the most relevant and original of them being the "expression" mechanism. In LTE-Direct, expressions are service layer identifiers and can represent an identity, a service, an interest, a location, etc. In the publish/subscribe paradigm, of central interest in D2D proximity discovery, an expression is what a publisher can broadcast (e.g., a device can broadcast an expression over the air for representing the information "we are a coffee shop").

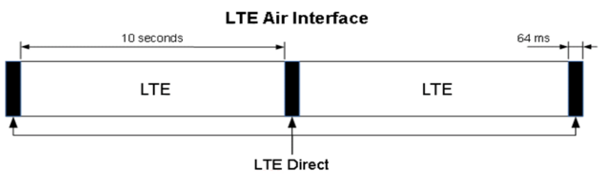

Figure 1: Example of resource allocation for LTE Direct: a period of 64ms for direct discovery is allocated every 10s of regular LTE communications.

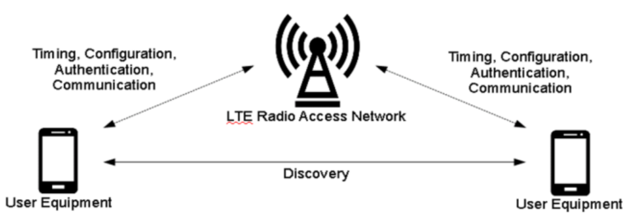

Figure 2: LTE Direct architecture.

An LTE-Direct expression consists of:

- name - an application-defined string used by the application layer;
- code - a shorter binary form of the name, used by the physical layer over the LTE Direct Over The Air (OTA) interface;
- metadata - extra data transmitted with the expression code over the OTA interface.

To receive this broadcast transmission, subscribers must not only be in "proximity" of the publisher, but must also have a key, called subscription key. Only the knowledge of that key allows receiving the related expressions. The subscription key is generated by the publisher with a one-way hash function starting from another key called publish key. This behavior assures that attempts like personification are not feasible: only the publisher (one or more) that owns the publish key can generate the correct OTA code that can be received with the specific subscription key. Note that an expression may have associated some metadata: if the expression code to be matched with the subscription key is typically used to represent the type of service offered by the publisher, the metadata can represent peculiar characteristic of that service (e.g., an expression associated with a shop discount advertise may have metadata describing the items in promotion and the related discount to apply). Another relevant point about the expression mechanism is that expressions are filtered at device level: applications are woken-up only when expressions matching their subscriptions are received, with positive effects on energy saving. In addition to simple subscriptions, LTE Direct also allows expressing filters (simple bitwise filters) on metadata; filters as well effectively work at the device level, thus enabling additional battery saving. Moreover, LTE Direct promotes a common framework to manage expressions, by making them application-agnostic: the framework is based on an entity called Expression Name Server (ENS) that maintains the mapping for the bits to text for an expression, thus supporting the length minimization of OTA messages. ENS is also used to store information about how to discover an expression: it is possible to "obtain" the subscription key of a given expression by sending a request to ENS with the name of the expression (already registered in the ENS). Those type of expressions are called public expressions, in contrast with private expressions that are application-specific and can be decoded/received only by devices that already own the associated subscription keys.

3 DESIGN AND IMPLEMENTATION OF OUR MULTI-FRAME TRANSFER PROTOCOL

In this section we present our original protocol for data dissemination over D2D proximity discovery. The main idea is to exploit discovery advertising messages for data dissemination to proximity listeners notwithstanding the length limitations that these messages usually have, typically for power saving motivations. Note that length restrictions in D2D proximity discovery messages are generating usage scenarios where participants share an a-priori and typically static common knowledge and where every transmitted bit has an application-specific meaning that can be understood only thanks to this static common knowledge. For example, BLE adopts the GATT (General ATTribute) specification for that, which includes already defined profiles such as for battery indicator and heart rate monitor data. Also LTE-Direct has a similar approach with Public Expressions: in this case the specification is maintained by a server and subscribers have direct access to the specification data to interpret "on the fly" the received bits. However, even when adopting these countermeasures, the amount of information that can be exchanged in a single discovery period remains small and the above work demonstrates the awareness of the associated limitation.

Differently from what already explored in the recent related literature, we have decided to originally investigate a multi-frame transfer protocol solution that clearly separates the transmission layer represented by the underlying D2D proximity discovery technology and the higher layer where possibly long messages are managed; in other words, in a transparent way from the perspective of the application layer, our protocol is able to broadcast data with no length limitations over multiple discovery periods in an effective and efficient way. The characteristics and features of the proposed protocol, moreover, are designed to fit the requirements of application domains of emerging relevance in the field, such as vehicular data dissemination and coordination. In particular, consider a scenario where there are several LTE Direct spots along the way, which periodically publish useful information for vehicles passing-by (e.g., traffic information or alerts in general). Our multi-frame transfer protocol can allow a vehicle to start receiving chunks (frames) of the information from one spot and continue receiving it from other spots, by seamlessly discarding duplicates and reconstructing the application-layer message even from multiple sources. In addition, it is possible to envision the usage of the vehicles themselves as frame repeaters (this type of interaction is currently not allowed in the standard LTE Direct specification), in order to maximize transfer rate and to virtually extend the spot transmission coverage.

3.1 Multi-frame Transfer Protocol for LTE Direct

Our protocol is developed on top of LTE Direct, but can be easily applied to every D2D proximity discovery solution adopting the publish-subscribe paradigm. It is also important to state that this protocol is particularly intended for scenarios where a de-vice (publisher) emits some information periodically and other devices (subscribers) can listen to it without any feedback to the sender. For instance, consider the case of a shop that advertises its promotional offerings to possible customers in proximity; in an "always-on" discovery scenario the advertising dissemination will be periodically repeated, also to cover different potential customers passing-by and dynamically changing.

In LTE Direct, an expression is the atomic unit of communication and generally maps a single information. An overall expression, by referring to 3GPP Release 12, consists of 184bits, a fraction of which are available for additional data apart from the expression code. This practically means that, in the case where a device is willing to send an arbitrary string inside an expression, its length will be limited to less than 20 characters (using an 8-bit character encoding). To overcome this limitation, our protocol splits the application-layer message data, if necessary, into frames included in multiple expressions, by adding some metadata to efficiently rebuild the application-layer message at the receiver. Our solution has been partially inspired by the well-known ISO-TP approach, which is a standard protocol for sending data packets over CAN bus, by allowing transmissions that exceed the maximum payload size of CAN frames [24]. In particular, our protocol defines four type of frames (see Table 1):

- SINGLE is a frame that contains all the info transmitted (payload + data length);
- FIRST is the first frame of a multi-frame transmission and contains the length of the entire data transmitted, as well as the first chunk of the information;
- CONSECUTIVE is one multi-frame transmission frame, different from the first one, and contains both its data chunk and an index to represent the chunk position in the overall multi-frame message;
- CONTROL is a frame for hash-based evaluation of message integrity.

Table 1. Frame structure in our multi-frame transfer protocol.

Byte Offset	0		1	2	3	4	…
Bit Offset	0-1	2-7	8-15	16-23	24-31	32-39	…
Single	0	size (max 64) in bytes	non-split data				
First	1	size (max 16384) in bytes		first part of the data			
Consecutive	2	index (max 16384) of the frame		I^{th} part of the data (where I is the index of the current frame)			
Control	3	total number of frames (max 16384)		Hash of the data (e.g.: crc32)			

Any frame contains a header that describes the frame itself, by specifying frame type and overall message length. In the case of a single-frame transmission, the first byte will be the header. The first two bits of the header represents the type of the frame, the remaining six bits contains a positive integer number that represents the length in bytes of the data transmitted. Using six bits to express data length imposes a limit of 64 bytes of data that can be transferred. This limitation is anyway compatible with most of the D2D proximity discovery technologies available or under specification and allows minimum header size. Anyway, we have designed the protocol so that it will be easy to extend the header size in the future. If message length exceeds the single frame, header included, the data will be prepared to be sent with multiple frames (see Fig. 3). The first step is to partition data according to the capacity of a single frame; if N is the number of parts in which the data is split, there will be N+1 frames to be sent by including also the CONTROL frame to for data integrity.

A relevant feature of the proposed protocol is that it can handle frame sending/receiving correctly independently from their order. This is particularly relevant in high-mobility scenarios where frames can be lost for many reasons (interference in communications, absence of direct connection, etc.) and a simple periodical retransmission of all the information by the publisher (or the set of collaborating publishers) allows the subscribers to retrieve the missing frames. The order irrelevance leads also to another advantage: the possibility to publish different pieces of the same data with different devices at the same time, for example to obtain improved transfer speed. Let us finally note that correctness is guaranteed even if the publisher starts transmitting a different message before the full reception of the previous message at some receivers thanks to the integrity check.

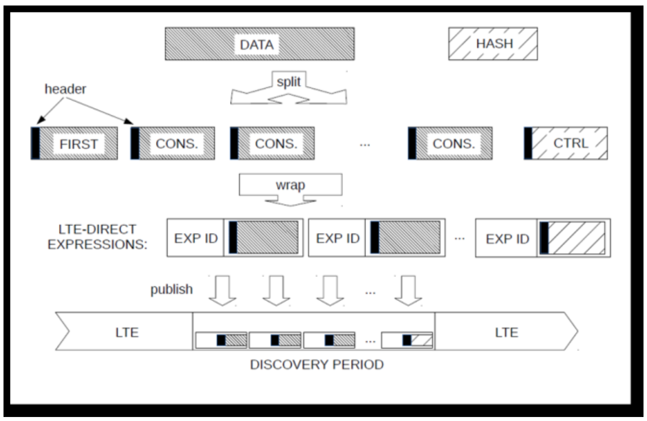

Figure 3. Multi-Frame protocol publish mechanism using LTE Direct expressions.

3.2 Implementation Insights

Our multi-frame protocol implementation code, together with additional implementation details omitted here for the sake of briefness, is available at http://lia.disi.unibo.it/research/MFTP_for_ProSe. To validate the protocol, we used the LTE Direct Trial SDK by Qualcomm Technologies [20], available for Android and iOS. This SDK allows developers accessing all the features to create, publish, subscribe, and manage LTE Direct expressions. In addition, the Android version of the SDK includes an LTE Direct simulator service that can emulate the presence of LTE Direct on the Android devices where the service runs on.

The first step in our validation work was to create a software module to manage the multi-frame transmission according to our protocol. In particular, this module allows specifying the size of a single frame that can be transmitted (this parameter is technology-dependent) and offers two functions:

- starting from the data length to be transmitted, it creates the corresponding frames based on the multi-frame protocol and the single frame dimension;
- rebuilds the original data bytes from the previous group of frames, by verifying their integrity via the hash described previously.

As depicted in Fig. 3, for the publish operation, our module simply splits the data bytes in the corresponding frames, builds the correct associated expressions, and publishes them on LTE Direct (in the case, frames are automatically distributed among different discovery periods).

The subscription part of the module works on receiving the expressions/frames and elaborating the included information. In particular, for each frame:

- if a frame of type FIRST is received, its payload is stored like the first part and in-formation is extracted about the size of the whole message. The reception of different type FIRST frames, before the completion of previous message reception, is supported and multiple messages can be received and processed concurrently;
- if a frame of type CONTROL is received, our module stores its payload (which rep-resents the hash of the entire data) apart;
- if a frame of CONSECUTIVE type is received, our module extracts the frame index from the header and uses it to store the payload in the correct position efficiently. If another CONSECUTIVE frame of the same message with the same index is received, we have decided that the new version overwrites the old one.

When all the frames are received, the original data is restored using the data length inside the FIRST frame header and the payload of all the frames received. If the re-stored data passes the integrity check, the data can be considered successfully received, otherwise the reception process for that message will start again.

4 EXPERIMENTAL VALIDATION

Our protocol implementation on top of the LTE Direct Trial SDK, originally presented for the first time in this paper, has been validated through different tests. First, we have verified the correctness of our multi-frame protocol when reconstructing messages with randomly generated frame repetitions.

Second, we have employed the LTE Direct simulator service for validation over real Android devices: the simulator service by default is configured to allow 32ms of direct discovery every 5s (this configuration is fixed and cannot be changed in the current version of the simulator service); LTE Direct allocates one sub-frame every 1ms; the LTE Direct simulator allows a device to publish one expression every sub-frame. In the first experiment we have used one only device to publish a message via our multi-frame protocol and two devices subscribed to it. Then, we tested a more articulated and challenging execution environment where two devices publish the same message concurrently: the associated peculiarity is that the entire message consists of more than 32 expressions, so it exceeds the number of expressions per device allowed for a single discovery period; this means that the entire information published by one device requires at least two successive discovery periods to be transmitted and correctly received. We have verified experimentally that the availability of two publisher devices allows overcoming this limitation: e.g., publishing the same frames, in the same time interval but not in the same order, by two devices allows subscribers to receive the entire set of frames even in only one discovery period in our tests. This points out and assesses another relevant feature of our protocol (see Fig. 4): using more than one publisher to transmit the same message can augment the perceived data rate at subscribers, of course within the boundaries of total traffic admitted by LTE in a proximity.

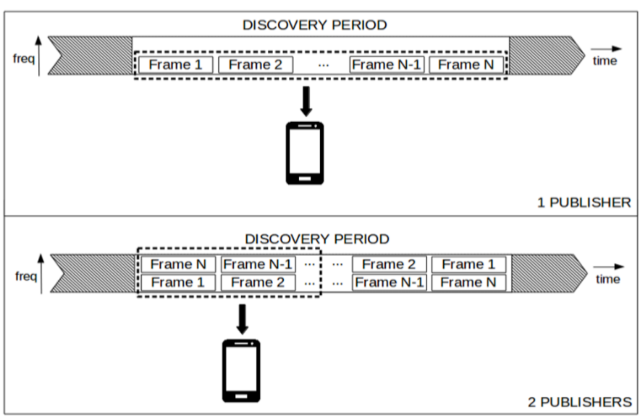

Figure 4. Validation tests with the LTE Direct simulator show the possibility to halve the reception time by using two publishers of the same information with frames in reverse order.

6 CONCLUSIVE REMARKS AND ONGOING RESEARCH WORK

This paper originally presents a protocol for D2D proximity discovery that allows to disseminate application-layer messages in proximity localities, even if the message length exceeds the single discovery transmission frame (as commonly occurs due to the strictly limited length imposed by standard D2D proximity discovery communication mechanisms). Even if a direct communication between devices would be possible using other technologies such BLE and Wi-Fi direct (and in the future also a specific feature for LTE Direct is expected), this protocol allows putting together the advantages of an always-on battery-efficient discovery solution, such as the one in LTE Direct, with the opportunity of broadcasting application-layer messages of reasonable length.

The presented protocol, although developed on top of the LTE Direct technology, is intended to be technology-agnostic and can be applied to all D2D proximity discovery scenarios. We have opted for the implementation of an LTE Direct prototype because we believe that LTE Direct is the most promising technology in this field at the moment; being still in its development stage, in this work we had only the opportunity to validate and assess our solution over the indicated SDK and simulator. However, initial experimentation tests by Qualcomm in collaboration with Deutsche Telekom and Huawei, recently presented in [22], confirm our performance observations based on simulations and the deriving expected behaviors.

Given the first encouraging results presented in this paper, we are pursuing two primary directions of related extension work: the former is oriented to experimentation in a real test-bed as soon as it will be available; the second relates to performance and robustness assessment while growing the probability of different types of interferences and disconnections (with consequent increase in frame loss probability).

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