Ad-hoc links in cellular networks for public safety communications

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Résumé – Les réseaux cellulaires subissent une augmentation rapide des demandes en termes de débit et de qualité de service. Pour soulager les contraintes sur ces réseaux, des communications autorisant les connections pair à pair entre des terminaux situés dans la même cellule ou dans des cellules voisines ont été proposées récemment. Ces communications qui sont sous le contrôle de l'opérateur du réseau cellulaire vont permettre d'offrir des services mobiles à proximité des utilisateurs tout en allégeant la charge sur le réseau principal. Ces nouveaux modes de communication peuvent aussi être étendus vers des communications ad-hoc qui pourraient servir pour les services de sûreté publique dans les scénarios de crises. Cet article présente les cas d'usage des communications pair à pair dans les réseaux cellulaires ainsi que les moyens d'implémentation de ce mode de communication dans les futurs réseaux LTE.

Abstract – Cellular networks are evolving to an increasing number of applications ranging from simple voice calls to video streaming and data transfer. Recently, it has been suggested to extend theses networks to short range communications using device to device links. The aim of such type of operation is to alleviate the data traffic load on cellular networks, and also to provide an alternative option for public safety communications. This paper presents an overview of the potential applications of device to device links in cellular networks and also presents the technical challenges and the potential solutions to implement this feature in near future standards.

1. Introduction

Future wireless cellular networks aim to achieve high data rates (more than 1Gbps), large capacity and high QoS for millions of subscribers. The currently deployed systems follow a centralized infrastructure where the operators guarantee the coverage through appropriately dimensioned base stations. In order to satisfy the increasing demand in terms of data rate and capacity, cellular networks have evolved to broadband technologies which employ large spectrum (5, 10, 20MHz). However, because of spectrum scarcity and a fast growing demand, cellular networks are evolving toward a layered topology where multiple layers of networks coexist with the main macrocell layer. Such approach allows to alleviate the traffic load on the macro network and also to offer better propagation conditions in special environments (indoor, tunnels etc).

As an example, a femto-cell layer on the top of a macro network enhances the data rates that are available to indoor users and at the same time mitigates the traffic load on the macro base stations. Recently, it has been proposed to add device to device layer on top of the macro and femto networks in order to offer proximity services for mobile users and also to reduce the traffic load on the fixed infrastructure. This functionality could be implemented using Wireless Local Area Network (WLAN) and Wireless Personal Area Network (WPAN) technologies operating in the ISM bands. However, such option which operates in unlicensed bands, suffers from non-controlled interference which limits the quality of service of direct links. The other option consists in implementing device to device communication on top of the technology that it used for the communication between mobile terminals and base stations. This choice implies a significant revision of the new cellular standards like LTE and 802.16. However, it allows a full control of the radio resources that are allocated to the device to device links, and consequently offers predictable quality of service. Moreover, appropriate ad-hoc communication techniques could be combined with this option in order to extend the usage of cellular mobile terminals for public safety applications. Such mode of operation could be enabled as a fall-back alternative in crisis scenarios where infrastructure is totally or partially disabled. Furthermore, this option offers advanced multi-media transmissions for rescuers (police, firefighter, heal staff …) which provide a significant positive impact on their missions.

This paper investigates the use of device to device communications in the context of the emerging version of the 3GPP LTE standard. The motivation for device to device links for public safety applications is first investigated. Then implementation options based on the recent literature are presented with a comparative point of view. Finally the impact of device to device links on the performance of a running cellular network is discussed.

2. Relevance of device to device links for consumer and public safety applications

In addition to extending the coverage of cellular network provider, D2D communication is attractive for a large number of use cases for consumer public safety and military applications.

2.1 Consumer applications

D2D communications offer new services by allowing User Equipments (UEs) to exchange voice, data and multimedia directly while being connected to cellular networks at a low-cost infrastructure. This communication mode is very convenient for mobile users in the same vicinity reducing thus the delay of their connections. At the same time, it is beneficial for the cellular provider since it mitigates the overall network load and saves radio resources for the UEs operating in legacy cellular mode.

On the other hand, D2D connections may be used in a mobile relaying mode where one terminal relays the exchanged data to the base station or to a destination D2D terminal. Such configuration improves the cellular coverage for the terminals experiencing bad propagation conditions or located in white areas. Hence, the terminal originally isolated can benefit from all the services allowed by the cellular operator thanks to the relay set through the intermediate terminal.

Figure 1 depicts the two aforementioned use cases.

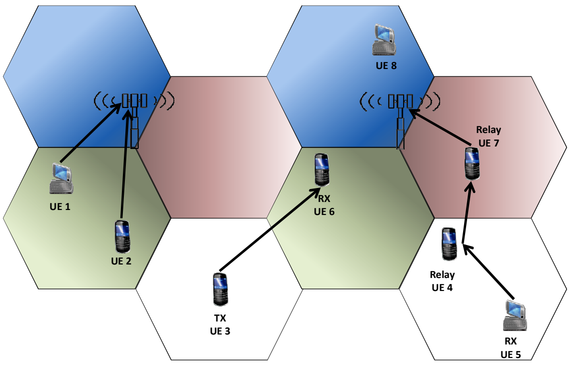

FIG. 1 : D2D usage cases

2.2 Public safety applications

D2D communications can be considered as an alternative option to replace the cellular network during a disaster or when the cellular network infrastructure is totally or partially disabled. However, the temporary D2D-based network cannot support an infinite number of UEs, it is only dedicated to the rescuers in order to coordinate their interventions.

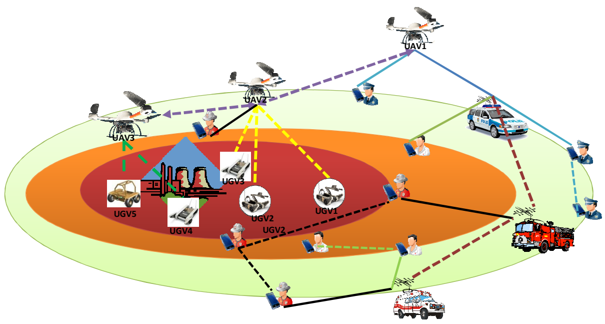

FIG. 2 : Example of D2D communication in a public safety application

In the example of a nuclear disaster, the rescuers need to exchange information (data, voice and video) to come over the crisis. They also need to deploy ground robots and unmanned aerial vehicles (UAV) in forbidden or unreachable zone for measure and monitoring. The exchanged information, measures or videos can be sent may be sent to different stakeholder groups who assess the risks, take decisions and help rescue teams in their missions.

The deployed robots can be equipped with a relaying device in order to relay information for distant rescue groups or for other robots in the unreachable zones.

Figure 2 shows an example of D2D communication between robots on the air and on the ground and between terminals of rescuers.

3. Device to device links in cellular networks

3.1 Implementation options for device to device communications

Device to device communications mode is being investigated as a new feature for next generation LTE systems [6][2][3]. Its main objective is to offer proximity services to mobile users while alleviating the load on serving base stations. Moreover, it requires two main functionalities, namely proximity discovery and direct communication.

The first option to implement D2D feature is technically feasible by relying on a heterogeneous network approach, where different wireless technologies are working together on the same device.

In fact, WLANs (IEEE 802.11) and WPANs (Bluetooth) are available in most modern mobile devices and can be employed to implement D2D feature in application layer. However, this option needs a significant amount of signaling in order to achieve proximity discovery service. Also, direct links will be made in unlicensed bands where interference cannot be controlled, limiting thus the interest of device to device communications because of an uncertain quality of service.

The other option to implement D2D links consists in employing the same technology that is used to communicate with the infrastructure. In LTE context, this implies that D2D links are performed on top of the OFDM(A) physical layer that is included in the mobile terminals. By operating in the licensed band, quality of service can be guaranteed provided that D2D links are controlled by the infrastructure.

3.2 D2D with LTE PHY

D2D communications require additional software and hardware functionalities at both mobile terminals and infrastructure sides. We present here the main functions to be implemented as well as the various possible implementation procedures and their impact in the context of LTE standard.

3.2.1 Resource sharing with D2D in TDD and FDD

Since device to device links will be considered as an overlay of the cellular network, they need to be coordinated in time and frequency with the legacy cellular links. The LTE standard supports two modes of duplex operation, namely Time Division Duplex (TDD) and Frequency Division Duplex (FDD). In TDD mode, D2D links can be overlaid with uplink slots, with downlink slots or with both.

From an interference point of view, the impact on legacy cellular communications is lower when operating in uplink slots. In fact, in this case, only the base station will suffer from interference, and such interference can be easily mitigated by using interference cancellation and MIMO techniques. When operating in the downlink slots, the resource allocation has to take into account the potential interference that is caused by D2D links on neighboring devices, since the interference cancellation capabilities of the mobile terminals are in general limited. Another approach in TDD and FDD modes consists in allocating dedicated time slots or frequency resources for D2D only operation. Even if is such approach deprives the cellular network from radio resources, it can offer a competitive preference when a significant fraction of the links are between devices that are in the same cell. This situation is particularly encountered in public safety scenarios.

3.2.2 Hardware

The additional hardware functionalities concern mainly the mobile terminals and depend on the duplex mode. In a TDD mode, uplink and downlink share the same spectrum, and the terminal has a transmitting (TX) radio frequency (RF) chain and a receiving (RX) RF chain in the same frequency band. As a consequence, there is no need for additional RF hardware for the mobile devices. However, FDD terminals have a receiving RF chain in the downlink band and a transmitting RF chain in the uplink band. In order to perform D2D links, they need additional RF stages which are a receiving RF chain in the uplink band and/or a transmitting RF chain in the downlink band. This gives an advantage to TDD terminals since D2D feature can be made for them with only a software or firmware upgrade.

3.2.3 Resource allocation and interference management

Additional software functionalities are required for both infrastructure and mobile terminals. From the infrastructure side, the time and frequency resources that are dedicated to D2D links have to be entirely controlled by the base stations. This is due to the fact that D2D links will operate in the licensed band that is exploited by the cellular network operator. Depending on the duplex mode (TDD, FDD) and the resource sharing option, the base station should be able to coordinate the time and frequency resources that are allocated to D2D links and to legacy cellular communications. The eNodeBs should also be able to control the transmit power that is used for D2D links.

When D2D links interfere with uplink cellular communications, the communication corresponds to the interference channel and appropriate interference cancellation techniques can be employed in order to limit the impact of this interference. Two types of solutions have been proposed: Strategies which consider interference as noise and which are based on appropriate resource allocation that minimizes the interference level between D2D links and the primary cellular communications. A significant number of techniques have been proposed for this purpose: iterative waterfilling [8], mixed integer optimization [4] …

The other type of solutions relies on physical layer approaches combined with MIMO processing at the transmitter and/or the receiver. A rate splitting technique has been proposed in [5]. With this approach, the transmit powers and rate splitting coefficients can be tuned so that interference cancellation is needed only at the base station side and not on the device to device receiving terminal.

When base station and mobile terminals are equipped with multi-antenna transceivers, it is also possible to employ linear interference alignment techniques so that the signals arriving to the base stations from the D2D link and from the legacy cellular user are included in orthogonal sub-spaces [7].

3.2.4 Proximity discovery

Another important functionality that needs to be implemented by the infrastructure is the proximity discovery. This function could be assigned to mobile terminals. However, it would require additional processing for scanning and signaling which may reduce their battery life.

According to [1], it is easier to detect proximity between mobile devices in the infrastructure. This can be implemented inside the gateway based on the routing tables and the IP addresses of the mobile devices. This option allows the infrastructure to control D2D links and also to decide if they are worth doing depending on the traffic load and the available radio resources.

3.2.5 Session management and handover

While D2D links can alleviate the traffic load on the cellular infrastructure, they introduce new handover overhead. In fact, because of user mobility and the short range of D2D links, a new handover scenario has to be considered between D2D mode and infrastructure mode. This handover can be initiated by the infrastructure which is also responsible for proximity discovery.

4. Performance of cellular network in presence of ad-hoc communication

The impact of D2D links on the primary cellular network has been evaluated in several contributions. It has been shown in [1] that when D2D links are established between devices in the same vicinity, a significant improvement (65%) can be seen on the aggregate cell throughput. This is due to the fact that D2D links will offload the cell from both uplink and downlink traffic which would be necessary if D2D links were established through the serving base station.

In [9], the interest of equipping mobile terminals with multiple antennas is investigated in the context where D2D communications are allowed as an underlay of cellular network. It is shown that simple linear interference cancellation schemes at the mobile terminal side doubles the number of possible D2D links compared to the standard case where all devices are equipped with single antenna receivers.

5. Conclusions

In this article, we have presented an overview of the use cases of D2D communications in the context of future cellular standards (LTE-A). D2D communications can increase the total capacity of a cellular network where a significant fraction of communications is held between user equipments in the same area. D2D links can also take advantage of good propagation conditions to offer high data rates, low latency and better battery lifetime.

We have described also the most important functionalities that are needed to get the D2D communication operational in LTE networks. Hardware implementation, resource allocation, signaling have been also discussed. The interference caused by D2D devices on cellular network has been raised and will be addressed in future studies.

6. Acknowledgement

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