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System Scenarios and Technical Requirements for Full-Duplex Concept

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Abstract: This document describes potential benefits of using full-duplex transmissions in wireless communication systems and identifies use cases for full-duplex utilization. Initial requirements for full-duplex transceivers are defined. Also initial set-up for the proof-of-concept demonstrator is presented.

Keyword list: full-duplex, scenarios, small cell, public safety

Executive Summary

The full-duplex communication principle, being able to transmit and receive simultaneously on the same carrier frequency, opens new possibilities for improving wireless communication system performance. However, it also sets challenging requirements for wireless transceiver implementation. The key challenge in implementing full-duplex based wireless systems is the self-interference caused by the coupling of the transceiver's own transmit signal to the receiver while attempting to receive signal sent by another equipment in a wireless network. If successfully implemented, full-duplex offers the potential to complement and enforce the solutions needed in the future evolution of wireless systems.

The full-duplex concept has gained strong attention in wireless communication because of its potential to sustain the vast evolution in traffic demand and variability with limited resources. Several publications indicate potential solutions at protocol layer and report promising theoretical performance studies. Only few publications report practical designs of wireless systems, but essential solutions are still required to enable the implementation of practical full-duplex radios and systems. Unlike current available literature, the DUPLO project will focus on the study and design of full-duplex radios and systems, by considering realistic conditions and constraints, and will integrate the different solutions to obtain an operational validation platform.

As a first step in the project, WP1 investigates the application of full duplex in future-oriented mobile wireless communication networks and identifies the main design requirements and constraints. Based on the evolution in wireless communication networks towards small-cells and the value of public safety communication, these networks have been selected as the main area of interest for the project. For these networks different scenarios to utilize and exploit the full-duplex principle are identified and motivated in this document. These scenarios will be further explored for full-duplex opportunities in WP4

For a reliable wireless full-duplex communication, the self-interference cancellation requirement between the radio transmitter and its own receiver is extremely challenging. This requires a coordinated design over the different building blocks (antennas, analog circuitry and digital signal processing) to obtain a constructive behaviour with respect to the self-interference cancellation. This document reports the realistic radio requirements over the different network types and scenarios, and gives a preliminary distribution of the technical requirements over the different building blocks. These values are essential design targets for the activities in WP2-3. Also the preliminary set-up and requirements for the proof-of-concept demonstrator to be implemented in the project are defined. This work will be continued in WP5.

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Abbreviations

3GPP	3th generation partnership project
5G	5th generation
ACK	acknowledgement
AP	access point
BER	bit-error-rate
BFT	Blue force tracking
BPSK	binary phase sift keying
BS	base station
CMOS	complementary metal oxide semiconductor
CSMA/CA	carrier sense multiple access with collision avoidance
CTS	Clear To Send
CW	contention window
dB	decibel
dBc	power ratio in decibels referenced to power at carrier frequency
dBi	antenna gain in decibel referenced to isotropic antenna
dBm	power in decibels referenced to one milli-watt
DCF	distributed coordination function
DQPSK	differential quadrature phase sift keying
DUPLO	Full-duplex radios for local access project
E_b/N_0	bit energy/noise density
EDGE	Enhanced Data rates for GSM Evolution
EVM	error vector magnitude
f_c	carrier frequency in MHz
FDD	frequency division duplex
FDMA	frequency domain multiple access
FDR	full-duplex radio
FFT	fast Fourier transform
F_{GHz}	frequency in GHz
GHz	giga (10^9) Herz
GMSK	Gaussian minimum sift keying
GSM	Global System for Mobile Communications
h_b	BS antenna height in meters
HCF	Hybrid Coordination Function
h_m	UE antenna height in meters
HPSK	hybrid phase sift keying
HSPA	high speed packet access
IC	integrated circuit

IEEE	Institute of Electrical and Electronics Engineers
IF	InterFrames
IFS	inter frame spacing
ISM	industrial, scientific and medical
LTE	long term evolution
M2M	machine-to-machine
MAC	medium access control
MANET	mobile ad hoc network
Mbits/s, Mbps	mega bits per second
MHz	mega (10^6) Herz
MIMO	multiple input multiple output
NAV	Network Allocation Vector
OFDM	orthogonal frequency-division multiplexing
PA	power amplifier
PC	personal computer
PCF	Point Coordination Function
PDA	personal digital assistant
PI	3.14159
PMR	personal mobile radio
PTT	Push To Talk
QAM	quadrature amplitude modulation
QoS	quality of service
R	distance
RF	radio frequency
R_{km}	distance in kilometers
RRM	radio resource management
RTS	Request To Send
SIC	self-interference cancellation
SINR	signal-to-noise-and-interference ratio
SNR	signal-to-noise ratio
TDD	time division duplex
TDMA	time domain multiple access
TETRA	terrestrial trunked radio
TX	transmitter
UE	user equipment
WAVE	wireless access for the vehicular environment
WCDMA	wideband code division multiple access
Wi-Fi	WLAN products that are based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards
WLAN	wireless local area network
WP	work package

1. INTRODUCTION

1.1. Full-duplex wireless communication

The full-duplex communication principle (i.e., the same carrier frequency is simultaneously used both for transmission and reception at the wireless transceiver) opens new possibilities for improving wireless communication system performance, but also sets challenging requirements for wireless transceiver implementation.

The key challenge in implementing a full-duplex wireless transceiver is the large power level difference between transceiver's own transmissions and the signal of interest coming from distant source as illustrated in Figure 1. Powerful compilation of antenna, RF and baseband solutions are needed to combat successfully with such self-interference. Only then, the transceiver can simultaneously transmit and receive on the same carrier frequency, enabling several new ways of wireless communication between communication devices. In practice, the achievable self-interference cancellation capability is limited, and also depended on multiple system constrains such as the form factors of the wireless devices. Therefore, potential applications of the full-duplex communications are also constrained by the achievable performance of practical full-duplex transceivers.

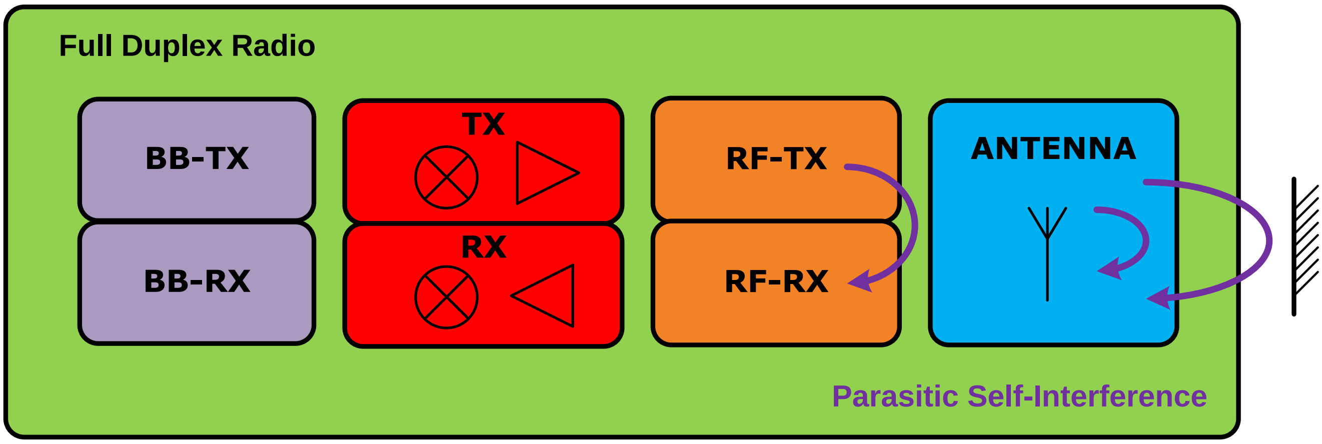


Figure 1. Self-interference problem in full-duplex system.

Full-duplex experimental demonstrations for narrowband wireless communication systems were first reported in 1998 [1]. Since then, several techniques and implementations have been developed [2-9] to accommodate the main challenges of increasing the self-interference and broadening the bandwidth. Only recently, reported results from the pioneering research conducted in Stanford University [4], Rice University [8], and Waterloo University [9] indicate that full-duplex wireless communications technology is approaching performance requirements of practical systems, and propose new ways of utilizing full-duplex communications in wireless communications networks. However, further work with full-duplex transceiver technology development, and full-duplex system applications and solutions is still needed to enable the introduction of full-duplex communication in practical and sustainable wireless communication systems.

1.2. Wireless communication systems evolution

The evolution of wireless communication systems is characterized by the need to support the vast growth in mobile data traffic and number of connected devices with limited spectral resources, and in an energy and cost efficient manner.

By the end of 2011, the number mobile communication subscribers corresponded to 86% of the world population with an annual growth of approximately 10 % during the last few years, and up to 40% for the mobile broadband subscribers [10]. This evolution is not bounded by the total world population, as multiple communication devices per users (smart phones, tablets, etc.) and self-operating communication machines (M2M communication) are increasingly common. It is expected [11] that by 2017, devices with a small form factor will be dominant, with 27.4% smart phones and 16.5% M2M communication devices. The global growth of the mobile data traffic is even more drastic; global mobile data traffic grew approximately 70% in 2012 [11], and it is expected to grow further with an annual rate of 66% during the next five years. A big portion of this data traffic will be consumed by smart phones, namely about 67.5% of the total traffic in 2017. The rest of the data is mainly consumed by laptops and tablets. It can thus be concluded that the mobile communication devices with a small form factor will be dominant by its number of connections and by its share in the total data consumption, and that the global data traffic load vastly increases. Laptops and tablets with larger form factor will also contribute significantly to the growth of this traffic.

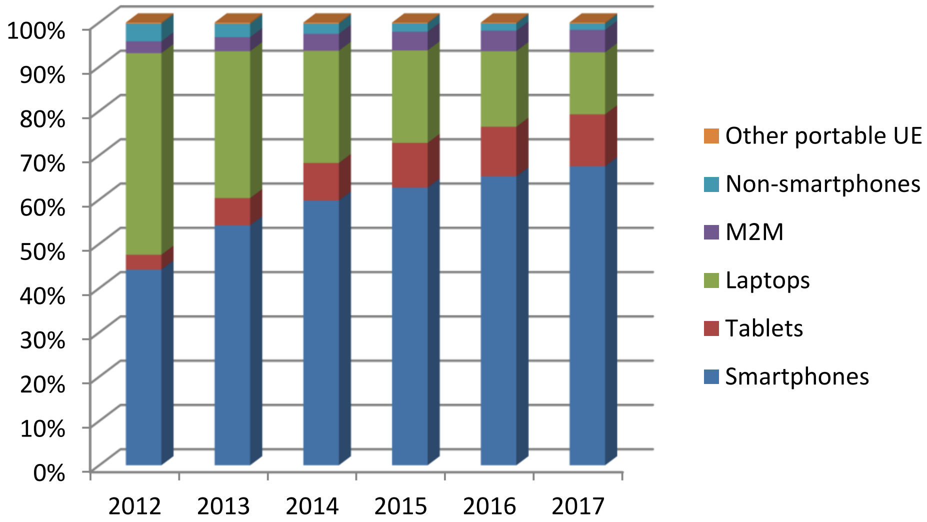


Figure 2. Relative distribution of the global mobile data traffic over different portable UEs [11].

The enormous data traffic volume is not the only challenge of mobile network evolution. The data traffic profile is also rapidly changing and becoming much more variable and less predictable over time and space. Some devices will always be connected to the network, but their traffic content will vary drastically. Such devices use their idle times (e.g. between e-mail push services) for other purposes such as exchanging messages, synchronizing data or posting updates on social networks. On the other hand, other devices such as M2M communication devices and sensors components of future Internet-of-Things will be connected only for small time instances and completely disconnected and eventually shutdown to save in power consumption. In addition to the data traffic variation, communication devices are increasingly mobile. The combination between this mobility and the variable traffic load is majorly challenging the network. Devices may move during their idle state, and although the network is not aware on their dislocation, it should always provide rapid access to connectivity. Signaling traffic should ensure such access and guide the data exchange between the mobile device and the network. It has been reported [19] that in 2010, the signaling traffic in Western European cellular networks grew with 177%, which is enormous even compared with the vast annual data traffic growth of 66%. This indicates the urgent need for more efficient access schemes, especially for devices with a varying data traffic profile.

A general trend in wireless communication systems evolution, and more particularly in radio resource usage, is to find solutions to improve spectral efficiency and flexibility in spectrum use. Vastly increasing capacity need in mobile communication networks combined with very slow pace of reallocating new spectrum for mobile communications requests for new solutions in using radio resources efficiently. Flexible use of spectrum e.g. with cognitive radio technologies [12], and data off-loading to WLAN networks [13] are examples of potential solutions to alleviate the problem. Improving spatial reuse of spectrum by employing inter-cell interference cancellation and multi-antenna transmission techniques are included 3GPP LTE technology solutions [14]. Introduction of new carrier types provide additional flexibility in spectrum use [14].

A major trend in 3GPP (LTE/HSPA) cellular network architecture evolution is the development of heterogeneous networks and small cells [14, 15, 16]. Heterogeneous network involves a mix of radio technologies and cell types working together seamlessly. Coordinated operation of macro cells and multiple small cells, eventually operating under the macro cell coverage area, enables the implementation of radio networks with good overall coverage and high local capacity. Small cells are considered to be the most essential element in the network architecture to get significant improvements in spectrum efficiency [14, 15, 16]. However, heterogeneous networks also pose new challenges. Due to the large number of small cells, mobile communication devices are handed-over more frequently between different cells, especially with the increased mobility. In addition to seamless hand-over of active devices, idle and new devices should be connected efficiently and transparently.
Other trends in wireless communications system evolution, some of which are partly related to 3GPP systems and ongoing standardization, include device-to-device communications, machine-to-machine communications, relays, wireless backhauling, mesh networks, etc.

Recently, interest and new initiatives in starting research activities to develop '5G' technologies have been arising, e.g., European Commission has announced to invest in '5G' technology development [17].

Currently, there is no exact definition of the '5G' system and technology contents, but as an example, following kind of targets and potential technology components have been proposed [18]:

- system concept that supports 1000 times higher mobile data volume per area, 10 to 100 times higher number of connected devices, 10 to 100 times higher typical user data rate, 10 times longer battery life, 5 times reduced end-to-end latency

- potential technology components including device-to-device communication, massive machine communication, moving networks, ultra dense networks, ultra-reliable communication

1.3. Sustaining the evolution by means of full-duplex

The fundamental feature of full-duplex communications is the possibility to transmit and receive simultaneously on the same carrier frequency. This feature offers the potential to complement and enforce the solutions described in the previous section, and to develop new systems to strengthen the sustainability of future communication.

The full-duplex feature can be utilized in wireless communications systems in multiple ways, including

- increased link capacity
  - theoretically, full-duplex doubles the link capacity with respect to traditional half-duplex, because the available spectral resources can be fully utilized in time and frequency.
- enabling introduction of novel and efficient channel access mechanisms
  - full-duplex capable wireless device can simultaneously listen the radio channel while transmitting signal to access point in order to probe if other transmissions occur in the same radio channel. This would enable fast collision detection in system.
- reduced air interface delay
  - simultaneous reception of feedback information (control channels, signaling related to error correction protocol, etc.) while transmitting data, enabling shorter latency in data transmission.
- more flexibility in spectrum usage
  - same frequency resources can be used for one directional transmission or bi-directional transmission. In the case of bidirectional transmission, the transceiver can communicate with one (full-duplex) or two different communication devices
- novel relay solutions
  - reuse of spectrum resources and thus enable almost instantaneous retransmission
- improved ad hoc and mesh network operation
  - full-duplex transmission could potentially enable to get rid of ‘hidden node’ problem typical for mesh networks
- improved security in transmission
  - two transmit signals mixed on the same carrier ➔ complicates eavesdropping

In practice, potential applications of the full-duplex communications are constrained by the achievable performance of full-duplex transceivers. In small area wireless communication systems, the power level difference between the transmitted signal and the received signal from distant source is relatively small enabling potentially use of full-duplex transceivers with small form factor. In some other scenarios, e.g., communications between base stations, full-duplex transceivers may have more capabilities, enabling also use of large communication distances. In the DUPLO project, different system scenarios have been considered as potential application areas for full-duplex communications, and therefore selected as the further research framework, i.e.,

- small cell wireless communications systems
- ad-hoc and mesh networks
- UE relay and wireless backhaul in public safety networks

Full-duplex communications principle can be utilized in multiple ways in these scenarios, as discussed further in this document.

1.4. Structure of the document

This document has been prepared in Scenario and Requirements work package (WP1) of DUPLO project. It identifies scenarios for the utilization of full-duplex transmissions in wireless communication systems and how the introduction of full-duplex principle can improve the performance in these scenarios. The work of WP1 serves as a starting point for the research of other work packages. Analog self-interference cancellation is considered in WP2, digital techniques are developed in WP3. In WP4, performance of wireless systems using full-duplex principle and protocol design for full-duplex systems are investigated. Performance of techniques developed in DUPLO project will be verified by building a proof-of-concept demonstrator. Initial set-up and requirements for the proof-of-concept transceiver design are also defined in this deliverable.

The principle of full-duplex in wireless communication is introduced and motivated in chapter 1.

Chapter 2 introduces different system aspects related to usage of full-duplex communication principle in wireless communication systems, and provides a state of the art review on protocol layer solutions for full-duplex communications.

Chapter 3 introduces the system scenarios selected as the research framework in the DUPLO project.

Chapter 4 discusses design requirements and constraints related to full-duplex transceiver research and system level research. Initial performance requirements for full-duplex transceiver are derived both from information theory and communication system basis. Initial description of the DUPLO proof of concept set up is provided. Furthermore, different constraints of practical devices are also discussed.

Finally, chapter 5 provides summary and conclusions on the DUPLO project full-duplex scenarios and work requirements.

2. FULL-DUPLEX LINKS AND SYSTEMS

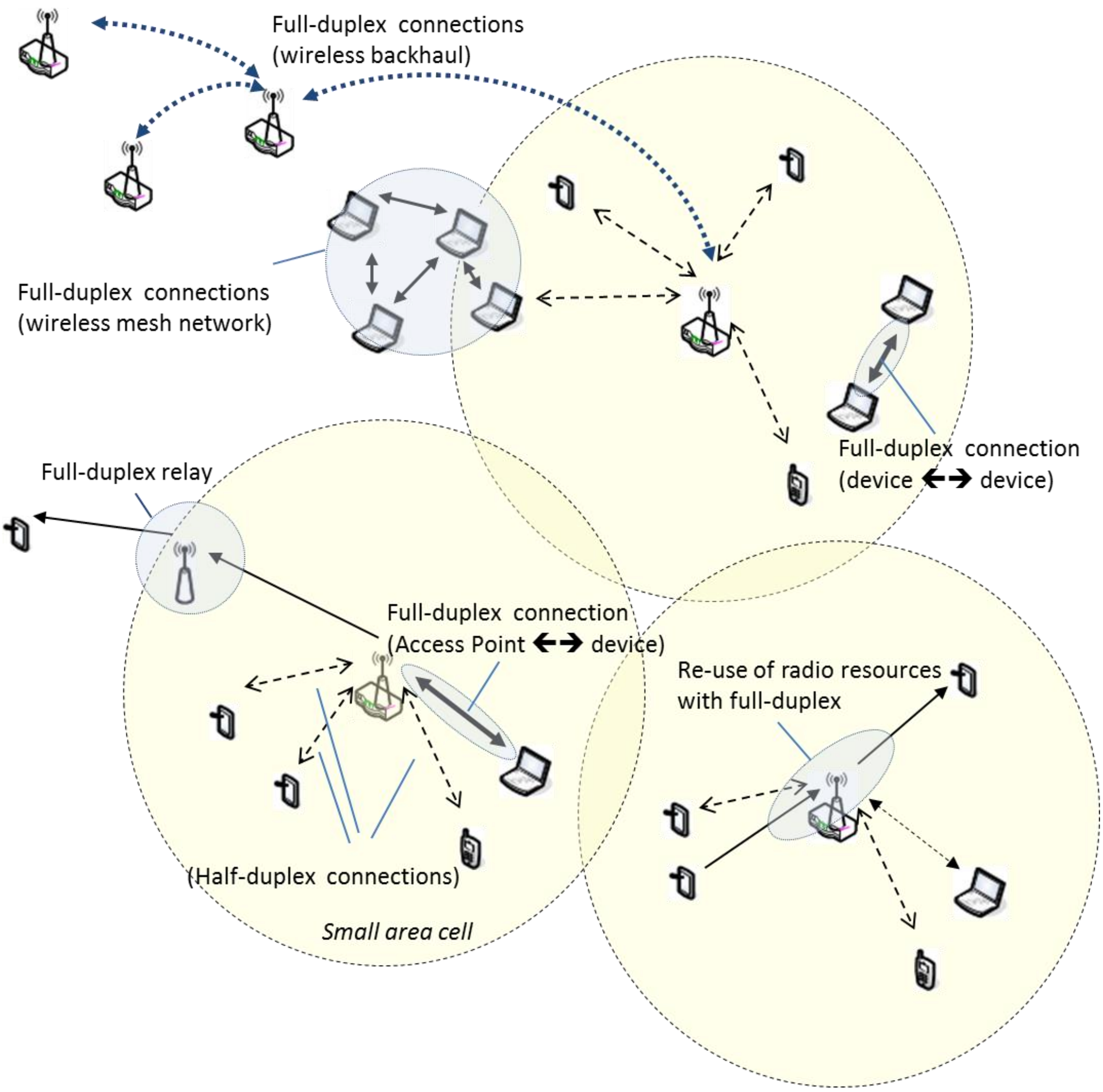


Figure 3. Wireless communication system

In Figure 3, a wireless communication system is presented. The large geographical coverage is attained by the cellular network. Cellular network can have different cell sizes depending on the operating environment and traffic demands. The most potential application of full-duplex technology in cellular systems is in small cells as discussed in chapter 3 of this document. Also in the figure, a mesh network is shown. In this case the nodes in the mesh network can communicate directly with each other using, e.g., IEEE 802.11 network. One of the nodes in the mesh network can serve as an access point to offer connection to the other 802.11 networks or infrastructure network (cellular network in the case of Figure 3). Further, device-to-device link is shown in the figure. Device-to-device communication is the probably easiest application area of full-duplex since it does not require complex network protocols. The wireless backhaul connection in the upper left corner of the Figure 3 probably gains less from the full-duplex principle than other network types. This is because the transmission powers can be higher in backhaul connections causing high levels of self-interference. On the other hand, if backhaul links are using high frequency (e.g., 60 GHz) it enables the use of highly directional antennas to help in self-interference cancellation.

Different ways to utilize full-duplex transmissions, especially in small cell environments and public safety systems are covered in Chapter 3. The rest of this chapter presents general issues of wireless networks and the effect of full-duplex technology on them. The discussion below serves as a starting point to the theoretical work to be done in work package 4 ‘Full-duplex systems’ where the impact of full-duplex principle on wireless communication systems and networks is considered.

2.1. Performance metrics for full duplex networks

All current wireless communication systems have been designed assuming time division or frequency division duplexing, i.e. reception and transmission of a radio device are separated in time or frequency. This assumption was used, e.g., in [20] when theoretical limits of obtainable throughputs for a node in a multi-hop or ad hoc network were formulated. Hence, the half-duplex assumption has had a fundamental effect across the protocol layer designs of wireless networks. This means that, in addition to hardware design, the introduction of full-duplex transmissions can have drastic impact on the system design. These possible impacts have not yet been investigated in a systematic manner.

At physical layer the obvious gain from full-duplex is the doubling of the sum capacity or spectral efficiency in a point-to-point link assuming perfect self-interference cancellation. But throughput is not the only quality of service (QoS) parameter. Full-duplex can have effect on, e.g., packet delay. Delay requirements might be more challenging to meet than data rate requirements in voice or other real time applications. Also for the network capacity, the throughput of a single-link is an important but only one factor. Network layer capacity is affected also by routing, scheduling and resource allocation protocols [21]. These various individual design problems are highly interdependent [22] making the analysis of the effects of full-duplex on wireless systems a demanding task.

In order to start the assessment of the effects of full-duplex transmissions on wireless systems the effect of full-duplex in different performance metrics can be considered. Metrics used to measure the performance of wireless systems are listed, e.g., in [23]. Although [23] considers routing in mobile ad hoc networks (MANET) those metrics are generally used in wireless systems research and design. The relevant metrics for full-duplex transmission are listed below.

Physical layer:

- *Signal-to-interference* ratio or *signal-to-noise-and-interference ratio* (SINR) is the most obvious metric that is affected by full-duplex systems due to the strong self-interference caused by the coupling of node’s transmitted signal to its own receiver. Since self-interference cancellation cannot be perfectly cancelled the SINR at the input of receiver’s detector is lower when using full-duplex transmission than with half-duplex.

Link and medium access control (MAC) layer:

- Full-duplex transmission has the potential to reduce the *MAC delay* because the transceiver can start transmitting while receiving and since each transceiver can transmit both data frames and signaling messages, e.g. acknowledgements, while receiving packets.
- Full-duplex transmission potentially degrades the *link reliability*, because of the reduced SINR at physical layer which directly couples the transmitted signal to its receiver.

Network layer:

- *Achievable throughput* of a node can be increased since it does not have to stop transmitting for receiving data packets or acknowledgements of its own transmissions.
- *End-to-end delays* can be decreased since acknowledgements can be sent at the same time than packets are received. End-to-end delay has also effect on queue lengths in nodes. Queue lengths have effect on scheduling [24] and they can also affect routing decisions and admission control.
- *Node buffer space* requirement is potentially reduced since node does not need to stop sending for acknowledgement reception.
- *Delay jitter* may decrease since queuing delay can be potentially decreased since node does not need to stop sending for acknowledgement reception.
- *Packet loss ratio* can increase due to self-interference.
- *Energy expended per packet* can increase due to required self-interference cancellation.
- *Route lifetime* can decrease if node's power consumption is increased due to self-interference cancellation.

The above list does not include all the possible metrics or the effects of full-duplex transmissions. It can be considered only as a starting point in exploration of the benefits and challenges that result from full-duplex operation. It should also be noted that potential effects of full-duplex operation mentioned in the list are preliminary and they will be explored in WP4.. Further, the effects seen in different performance metrics and on different layers are interconnected. These phenomena will also be investigated in the work package 4 of the DUPLO project.

2.2. Protocol design in full-duplex networks

When designing protocols at different protocol stack layers or across layers one of the constraints used in optimization problem formulations is interference region. Typical interference models are protocol, physical and k-hop models [25], [26]. In all these models half-duplex operation is assumed. The protocol interference model is usually defined as the area where only one transmitter can send at a given timeslot as illustrated in Figure 4(a). Since in full-duplex case the receiving node can also transmit the model for the interference region in Figure 4(a) is changed to one illustrated in Figure 4(b).

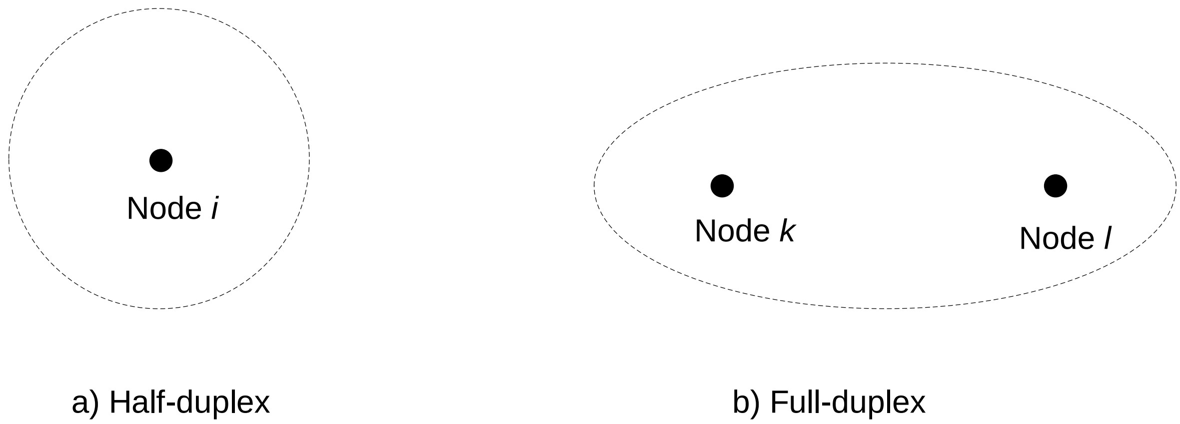


Figure 4. Interference region.

Interference region size is dependent on the node's transmission power. Full-duplex operation sets limits for the transmission power due to imperfect self-interference cancellation leading to receiver's limited self-interference tolerance. This decreases the interference region of a single node but at the same time also the range of the transmission. From network perspective the interference region in full-duplex system is composed of interference regions of the two transmitters involved in the full-duplex link.

Reduced transmission range due to full-duplex operation can result in the need of more hops in wireless ad hoc or mesh networks than using half-duplex operation leading to “long hop versus short hop dilemma“ [23]. This will have effect at least on the routing and topology control of the network. In general multi-hop approach results in increased collisions due to hidden nodes, inefficient bandwidth utilization due to exposed nodes and contention between locally generated and forwarded traffic [25]. However, full-duplex operation can mitigate hidden node and exposed node problems and it has also potential to increase the fairness [27].

MAC protocols should ensure efficient and fair sharing of the wireless bandwidth [28]. All current protocols have been designed using time division of frequency division duplexing. One consequence of this is that collision detection in the transmitting node is not possible. Hence, the most common starting point in MAC algorithm design in contention based system is the carrier sense multiple access with collision avoidance (CSMA/CA) principle. For example the distributed coordination function (DCF) of the IEEE 802.11 standard (Wi-Fi) is based on this principle. Full-duplex capable transceivers can offer the possibility to design also MAC algorithms using the collision detections. This could e.g., speed up the recovery from collisions resulting in increased network capacity. Full-duplex transmission can also reduce MAC congestion, especially in star topology multi-hop networks [4].Full-duplex allows more users to be served simultaneously in an infrastructure based networks, such as cellular systems and infrastructure mode of 802.11, than in half-duplex systems. It also makes uplink and downlink channels truly reciprocal apart the effect of transceiver non-idealities. Channel reciprocity can be useful in radio resource control. But since uplink and down link transmissions occur at the same time slot scheduling for both directions become tied together when full duplex transmissions are used. Interference at base station or access point and terminal can be different. In this case full-duplex can prevent scheduling algorithm from avoiding the usage of interfered frequency or time slots to mitigate the effect of interference. On the other hand the main application of full-duplex is most probably short range communication where interference can be similar at the both ends of the link.

2.3. State-of-the-art review

There has been increasing interest in full-duplex technology during the past year and the number of publications on the topic is increasing rapidly. However, most of the published work concentrates on the self-interference problem. Analog and digital techniques for self-interference cancellation are considered in work packages 2 and 3 of the DUPLO project and are not covered here. The utilization of the full-duplex concept at system level has gained less attention so far. Some full-duplex extensions of legacy protocols and also protocols specially designed for full-duplex networks have been already introduced but a systematic view on the utilization of full-duplex transmissions at the system or network level is still an open issue. The first published full-duplex MAC protocol (ContraFlow) has been described in [27]. It is a distributed MAC that is able to exploit self-interference cancellation. ContraFlow is based on dual-link principle: a primary transmitter sends a packet to primary receiver, as soon as the primary receiver detects the transmission it starts transmitting a packet or a busy tone. Primary receiver's transmission can be directed to the primary transmitter node (symmetric dual-link) or to a third node (asymmetric dual-link). The second component of the protocol addresses scheduling, i.e. how nodes attempt to use the channel. Nodes tune their access probabilities as function of the past proportions of time their own out-going links have been active (= successful transmissions). To work well, hidden terminal problem needs to be solved and this is addressed with the dual-link concept. Optimal scheduling would most probably require additional signaling. In the presented method optimality is deliberately sacrificed for simplicity. However, the algorithm improves both efficiency and fairness significantly when compared with standard CSMA and DCF and CSMA/DCF on the top of self-interference cancellation. The MAC used in [5] uses also the dual-link concept. In experimental tests full duplex has reduced packet losses due to hidden terminal by up to 88%. However, it should be noted that the test set up in [5] is a very simple network with 2 nodes and 1 access point. Using a 4 node, 1 access point fully connected network the MAC based on dual-links is reported to improve fairness from 0.85 to 0.98. It should be noted that the test set up is somewhat artificial and results should be considered to be preliminary. But they do show promising performance gains from using full-duplex transceiver based networks. In [29] a MAC protocol for full-duplex nodes using directional antennas is proposed. The proposed MAC gives 114 percent throughput increase in a line-type multi-hop network. A MAC protocol based on dynamic contention window control for a full-duplex access point based network is described in [30]. Introduced MAC protocol improves downlink throughputs without degrading input throughput. When there is less traffic in uplink than in down link the proposed protocol offers up to 2.4 times increase in down link throughput. This indicates that the potential benefit of full-duplex transmission at system level can be more than just the doubling of the link capacity.

The routing in full duplex networks is considered in [31]. In the article, two optimization problems are solved: 1) how to choose routes to maximize the total profit of multiple users subject to node constraints and 2) how to choose routes to minimize the network power consumption subject to the minimum user rate demands and node constraints. In [32, 33] a resource allocation problem is studied and a protocol for power allocation when nodes have self-interference cancellation capability is derived. Usage of full-duplex transceivers in multi-hop and fully connected networks is considered. In studied scenarios simulations show gain between 1.22 – 1.82 in average sum rate when using transceivers that are capable to self-interference cancellation over the case when nodes are not able to cancel the self-interference.

Most of the published works assume synchronous operation of the full-duplex system, i.e., node is able to estimate both the self-interference and desired channels before self-interference cancellation and data detection. Asynchronous mode of full-duplex operation is considered in [33] where it is shown that cases when a node is already receiving when it starts transmit and when node is already transmitting before starting receiving are feasible. This shows potential flexibility of the full-duplex transmissions.

3. SCENARIOS

3.1. Improving performance of cellular small cell wireless communications systems

3.1.1. Small cell characteristics

Small cell is a low-power wireless access point that operates in licensed spectrum [34]. In cellular systems, small cells are used to provide improved cellular coverage, capacity and applications for homes and enterprises as well as metropolitan and rural public spaces. Types of small cells include femtocells, picocells, metrocells and microcells – broadly increasing in size from femtocells (the smallest) to microcells (the largest). Figure 5 illustrates the different type of small cells used in cellular systems and their typical operation environments.

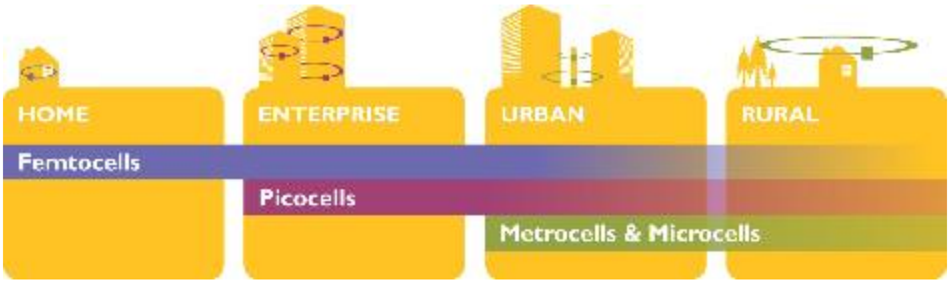


Figure 5. Small cell technologies and their typical operation environments [34].

There is no formal and unique definition for a small cell in cellular systems. However, the following definitions from multiple references in the literature [34-37] aim to clarify the differences between different types of small cells.

Femtocell is a small, low-power cellular base station, typically designed for use in a home or small business. Key attributes of femtocell include IP backhaul, self-optimization, low power consumption and ease of deployment. Typical range of femtocell is on the order of 10 meters, typical transmit power is 10dBm-20dBm, and typical number of users per base station is 4-6 users. Lately, the femtocell term has been expanded cover also higher capacity units for enterprise, rural and metropolitan areas. For example, term 'Public Space Femtocells' has been launched to describe public area femtocells having a cell radius of 10-100 meters, transmit power 0 dBm–24 dBm, and number of users per base station less than 20 [37].

Picocell is a low power compact base station, used in enterprise or public indoor areas. In some cases, picocell term is used to describe also outdoor small cells. Typical transmit power is 20dBm-24dBm (even up to 30 dBm), cell range on the order of 10 meters to 200 meters, and number of users per base station 30-100 users. A differentiating factor between picocells and femtocells is that picocells are deployed in coordinated manner by cellular operator while femtocells are deployed in more uncoordinated manner by the end user.

Metrocell is a recent term used to describe small cell technologies designed for high capacity metropolitan areas. Such devices are typically installed on building walls or e.g. on lampposts along the streets [34].

Microcell is and outdoor short-range base station aimed at enhancing coverage for both indoor and outdoor users. Typical transmit power is 33dBm-40dBm, cell range up to 2 km, and number of users per base station can be more than 100.

Another category of radios supporting wireless communications in local area is IEEE 802.11 technology based WLAN radios. IEEE 802.11 technology based systems are discussed in chapter 3.2.

3.1.2. Full-duplex enhancements in LTE type small cells

The primary target for using full-duplex technology in small cell operation environment is to *improve system spectral efficiency* through using the same radio resources for simultaneous transmission and reception in different nodes of the radio system. Full-duplex technology enables doubling of a single point-to-point link capacity in optimum case (symmetric traffic need in both directions, very high performance self-interference cancellation capability in both transceivers). Small cell system supporting multiple simultaneous connections between the base station and user devices can benefit from the fundamental advantage of full-duplex communications in multiple ways: i) using full-duplex communications for each base station – device connection separately, ii) using full-duplex communications principle in the base station to enable simultaneous transmission to one user device and reception from another device using the same spectrum resources , iii) using full-duplex technology for direct transmission link between two user devices, or iv) using different combinations above mentioned communication modes and conventional half-duplex communication modes.

Another mechanism to benefit from full-duplex communications in small cell operation environment is the potential ability to transmit system or link control information in one direction while transmitting user data to another direction. This could potentially provide improvements in system and individual link performance.

Achievable system capacity gain of full-duplex communications (over conventional half-duplex system, e.g., TDD system) in small cell operation environment is expected to be between 0 and 100%, depending heavily on various system parameters (e.g., traffic load between uplink and downlink, self-interference cancellation capabilities of transceivers in the base station and in user devices, system operation environment, etc).

In the following subchapters the discussion is limited to LTE femtocell and picocell kind of small cell systems. LTE TDD is considered as the main reference point when discussing full-duplex deployment scenarios and when evaluating potential gains of full-duplex technology in small cell operation environment. Femtocell and picocell systems are considered to be especially suitable for deployment of full-duplex technology due to used low transmit powers, short transmission distances (==> smaller difference in transmit and receive power, when compared to large area systems), and low mobility. The full-duplex use case examples discussed in the following subchapters refer to simplified models of the actual LTE TDD system. The examples in the following subchapters illustrate that radio resources for each BS-UE connection are given only in one dimension (i.e., either in time or frequency domain), while in actual LTE TDD system the resources can be given both in time and in frequency domains within one radio frame.

3.1.2.1. *Full-duplex capable BS and half-duplex UEs*

Due to the implementation complexity and the additional hardware cost, full-duplex technology may not be able to be implemented at UEs in the first phase but at a pico-BS or femto-BS. In this use case, the BS has full-duplex capability in order to improve the cell throughput. A straightforward idea is that a BS can receive from one UE while at the same time transmit to another UE on the same frequency band. For example in Figure 6, there is a BS communicating with 4 UEs individually, i.e. two downlink transmissions and two uplink transmissions.

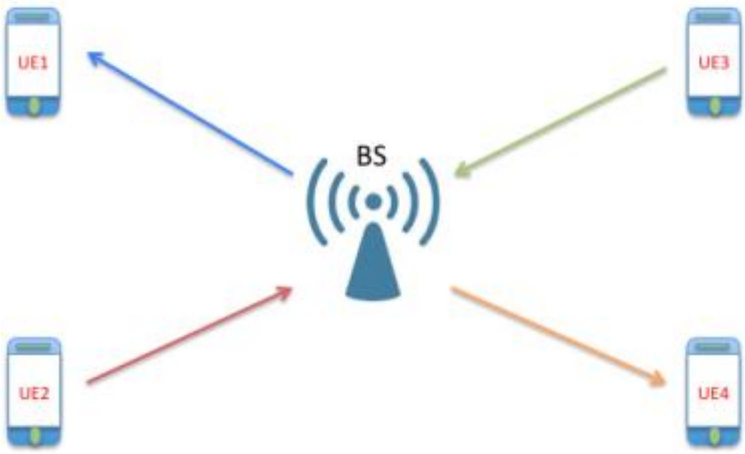
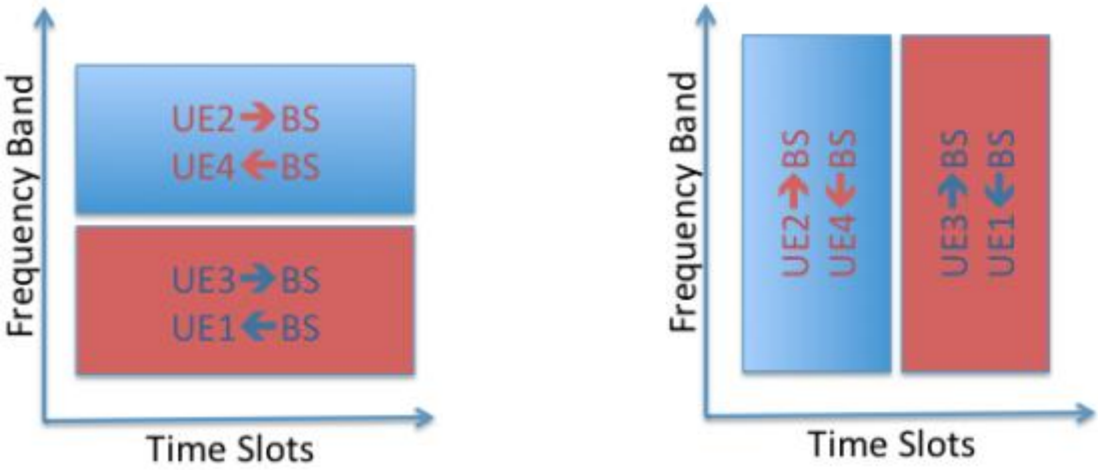


Figure 6. A LTE small cell with a full-duplex BS and half-duplex UEs.

If the BS is full-duplex capable, it may allocate two radio resources to support these four transmissions at the same time. Assuming the LTE small cell is using either FDMA or TDMA multi-user access scheme, the radio resource allocations are shown in Figure 7(a) and 7(b), respectively.



(a) FDMA multi-user access scheme (b) TDMA multi-user access scheme

Figure 7. User scheduling and resource allocation for a full-duplex BS with four half-duplex UEs.

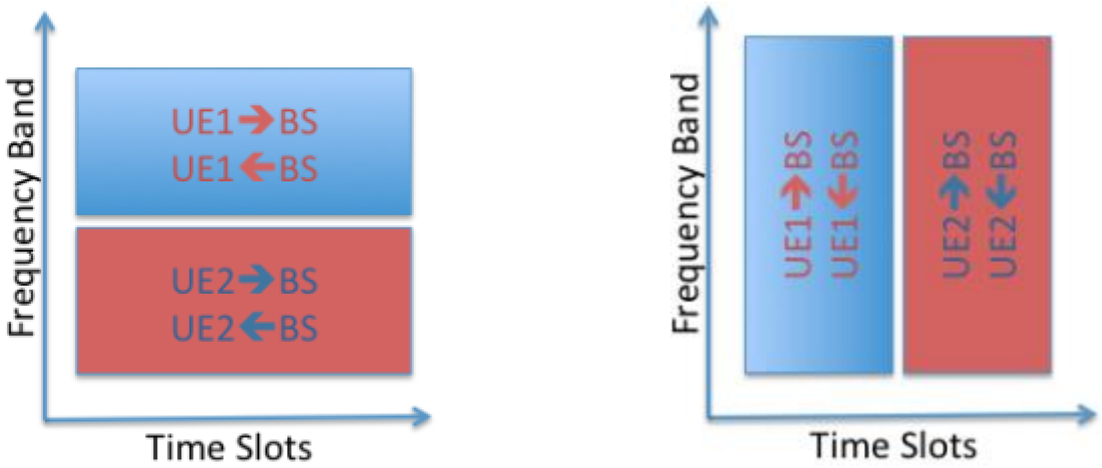
In this type of full-duplex applications, two interferences dominate the performance. The BS suffers the self-interference due to its own transmission. UE1 and UE4 suffer inter-user interference due to transmissions by UE2 and UE3. The first challenge is how to measure co-channel interference at different nodes and feedback it to the BS. In order to achieve the maximum gain, the BS must properly schedule a pair of the transmit UE and the receive UE being operated on the same resource. This requires a good and new design on user scheduling in LTE small cells, which is the second challenge. If FDMA multi-user access scheme is used, there are additional challenges. One further challenge is arising from the additional interference caused by the leakage of transmitted signals on neighboring band. This also affects operation with half-duplex technology. However in full-duplex mode, the strength of the leakage signals could be larger due to additional transmissions (i.e., simultaneous transmission on both directions) on the neighboring band. Another challenge is caused by the transmission of a nearby UE operating in adjacent frequency band. Although this neighboring UE is allocated to orthogonal frequency band in respect to the receive UE, its transmission power may still enter and saturate the RF chain of the receive UE.

3.1.2.2. *Full-duplex BS and full-duplex UEs*

It is also possible that in future both BSs and UEs in LTE small cells have full-duplex capability, as shown in Figure 8.

Figure 8. A LTE small cell with a full-duplex BS and full-duplex UEs.

An intuitive application in this scenario is that the BS always establishes a full-duplex link to the scheduled UEs. By doing so, each UE can transmit to and receive from the BS on the same radio resources, while different UE will use orthogonal radio resources. There are two examples shown in Figure 9(a) and 9(b). The first one considers FDMA multi-user access scheme while the second one considers TDMA multi-user access scheme.



(a) FDMA multi-user access scheme (b) TDMA multi-user access scheme

Figure 9 User scheduling and resource allocation for a full-duplex BS with two full-duplex UEs.

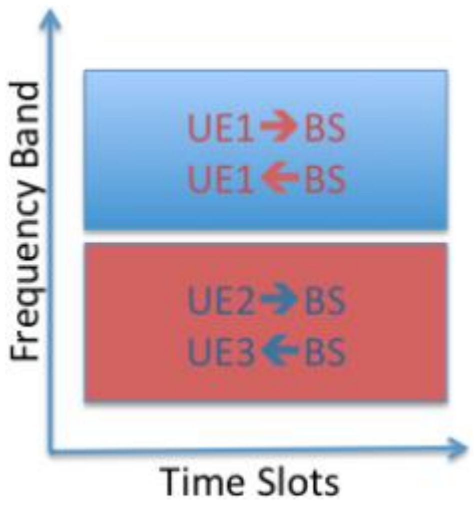
In this type of applications, there is no co-channel interference, in general. The self-interferences at both BS and UE side dominate the performance. Although it may not be necessary to measure the inter-user interference at UE side for scheduling purposes, self-interference measurement may still be beneficial. However, as the self-interference is more stable than the inter-user co-channel interference, user scheduling and resource allocation may be not as complicated as that of Section 3.1.2.1. Another challenge is related to the traffic load. Obviously, the user scheduling method shown in Figure 9 reaches the maximum gain when each UE has equal traffic load in both transmission directions. When the bi-directional traffic is not symmetric, a hybrid mode of Figure 7 and 9 may be applied. If this happens, co-channel interference problems may arise as well. Similar two additional challenges for FDMA multi-user access scheme as described in section 3.1.2.1 are also valid in this scenario.

3.1.2.3. *Full-duplex BS and co-existing full-duplex and half-duplex UEs*

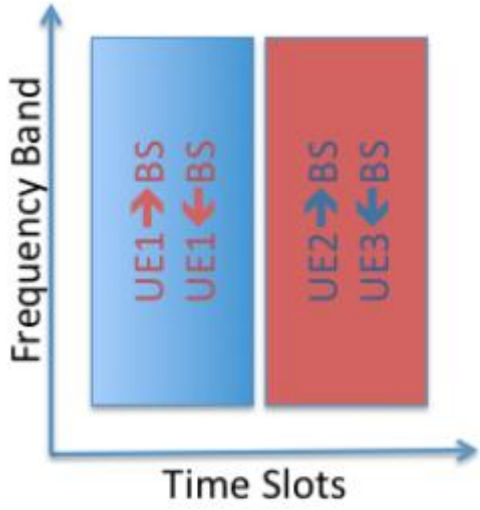
Another possible use case in future is that there are both full-duplex capable UEs and half-duplex capable UEs being served by a full-duplex BS, as shown in Figure 10.

Figure 10. A LTE small cell with a full-duplex BS and co-existing full-duplex and half-duplex UEs.

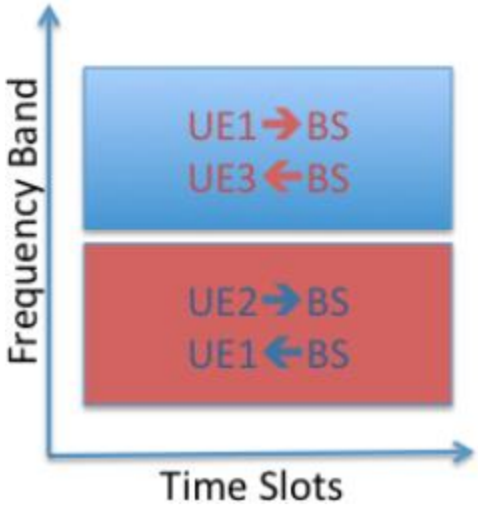
According to how full-duplex technology has been utilized, there are two possible user scheduling methods. The first method is shown by Figure 11(a) and Figure 11(b). With this method, the BS allocates a radio resource for UE1's transmission and reception, while it allocates another orthogonal radio resource for UE2's transmission and UE3's reception. It can be regarded as a hybrid mode of section 3.1.2.1 and 3.1.2.2 in general. The second method is shown by Figure 11(c) and 11(d). With this method, the BS allocates a radio resource for UE1's transmission and UE3's reception, while it allocates another orthogonal radio resource for UE2's transmission and UE1's reception. Generally speaking, it is an advanced modification of solution discussed in section 3.1.2.1.



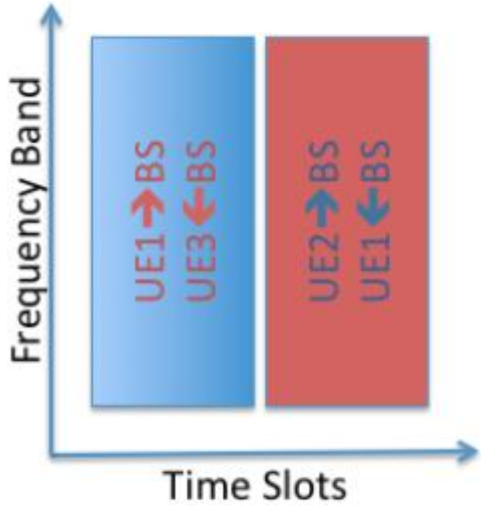
(a) User scheduling method 1 with FDMA multi-user access scheme.



(b) User scheduling method 1 with TDMA multi-user access scheme.



(c) User scheduling method 2 with FDMA multi-user access scheme



(d) User scheduling method 2 with TDMA multi-user access scheme

Figure 11. User scheduling and resource allocation for a full-duplex BS with two full-duplex UEs.

Similar challenge problems in Section 3.1.2.1 and 3.1.2.2 will be also valid in this scenario.

3.1.2.4. *Full-duplex device-to-device communications*

Device-to-device communications will be a new feature added into LTE release 12. The basic consideration is that two local UEs can communicate with each other on the unused macro resource if none of their neighbors are using it. A simple device-to-device communication set-up under a LTE cell is shown in Figure 12.

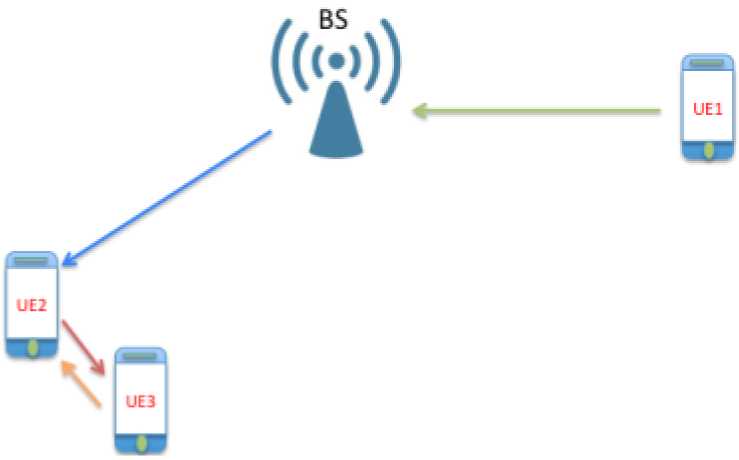
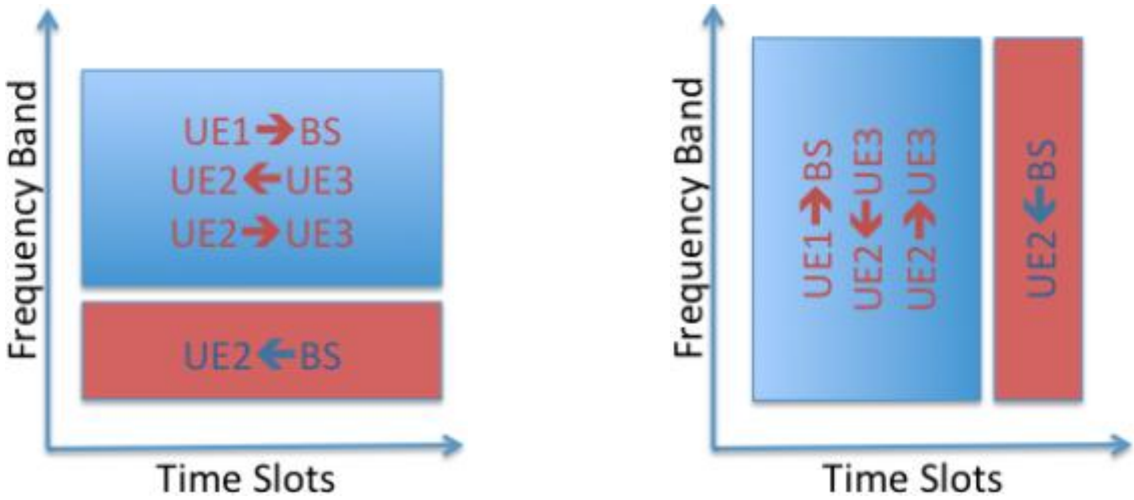


Figure 12. A LTE small cell with a BS and full-duplex device-to-device UEs.

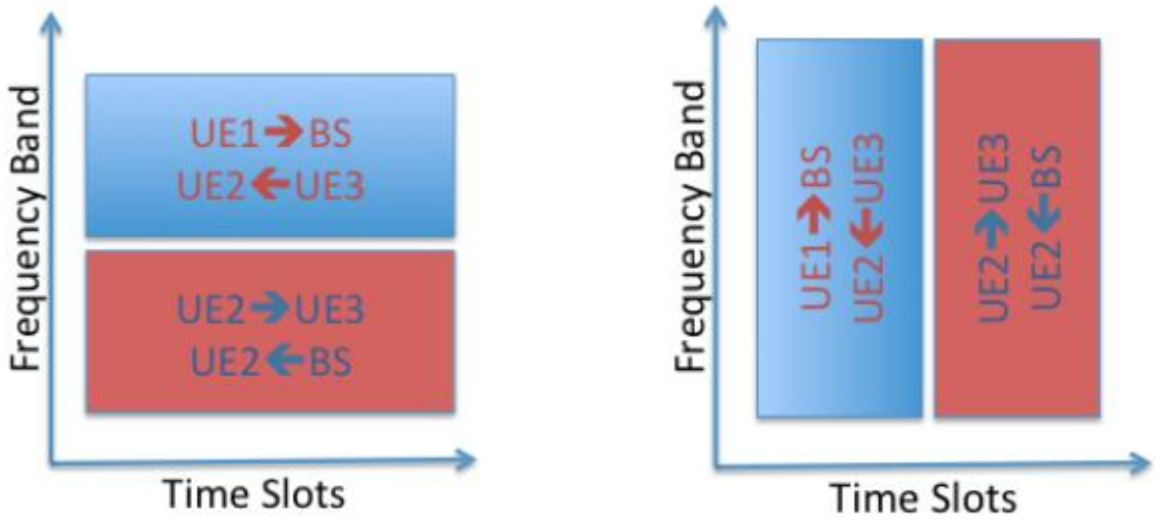
In order not to interfere macro cell communications, low transmission power is preferred in device-to-device communications. If UE2 and UE3 are both full-duplex capable, the performance of device-to-device communications may be further improved. For example in Figure 13, UE2 and UE3 are reusing UE1's uplink resources for their full-duplex communication.



(a) FDMA multi-user access scheme (b) TDMA multi-user access scheme

Figure 13. Full-duplex device-to-device communications: user scheduling and resource allocation method 1.

In case only UE2 is full-duplex capable, the communication between UE2 and U3 may get improvement by using another resource allocation method shown in Figure 14. In this method, UE2 reuses its macro downlink resources for its own transmission to UE3 while UE3 reuses UE1's macro uplink resource for its own transmission to UE2.



(a) FDMA multi-user access scheme (b) TDMA multi-user access scheme

Figure 14. Full-duplex device-to-device communications: user scheduling and resource allocation method 2.

Similar challenge problems in Section 3.1.2.1 and 3.1.2.2 will be also valid in this scenario.

3.2. Improving performance of ad hoc and mesh networks

3.2.1. IEEE 802.11 standard.

The IEEE 802.11 standard [38] comprises a physical layer and a MAC layer for random access in ISM (Industrial, Scientific and Medical) bands. This standard was adopted by the Wifi alliance in late 90's as the base of their commercialized wireless devices. From 1999 until very recently, numerous versions of this standard have been proposed allowing communications and access over the 2.4 and the 5 GHz unlicensed bands. In the following, we give an overview on this standard and its main constituting technologies

As already precised, this protocol can operate in the 2.4 and 5 GHz bands depending on the version and can achieve rates of 54 Mbits/s in widely deployed versions. It is worth noting here that some flavors of this protocol allowing even higher rates are being standardized, we do not cover these versions in this chapter. The table below summarizes most relevant versions of the IEEE 802.11 protocol.

802.11 protocol	Main characteristics
IEEE 802.11	the original 1 and 2 Mbps, in the 2.4 GHz industrial, scientific and medical (ISM) band, and infrared (IR) standard (1999)
IEEE 802.11b	enhancements to IEEE 802.11 to support 5.5 and 11 Mbps (1999).
IEEE 802.11a	operates in the 5 GHz band and allows throughputs from 6 to 54 Mbps
IEEE 802.11g	allows to reach higher data rates (54

	Mbps, identical to IEEE 802.11a) in the 2.4 GHz band. The orthogonal frequency-division multiplexing (OFDM) modulation is used. It provides backwards compatibility with 802.11b (2003)
IEEE 802.11d	international (country-to-country) roaming extensions (2001), access points (APs) communicate information on available radio channels and acceptable power levels, according to countries' lawful restrictions
IEEE 802.11c	bridge operation procedures, included in the IEEE 802.1D standard (2003)
IEEE 802.11e	enhancements (2005), standard for the quality of service (QoS), which defines the specifications of the QoS mechanisms to support multimedia applications
IEEE 802.11F	deals with the standardization of protocols between Aps to allow the use of a multivendor infrastructure avoiding proprietary standards.
IEEE 802.11h	spectrum managed IEEE 802.91a (5 GHz) for European compatibility (2004).
IEEE 802.11i	enhanced security (2004). Apply to standards IEEE 802.11 b/a/g
IEEE 802.1X standard	provides security mechanisms for various media including wireless links by the means of strong authentication procedures with dynamic key distribution
IEEE 802.11k	radio resource measurement (RRM) enhancements; it defines methods and measuring criteria needed by higher layer protocols to fulfill management and maintenance functions
IEEE 802.11n	higher throughput improvements; it offers higher data rates (108–600 Mbps) in the 2.4 and 5 GHz bands using MIMO
IEEE 802.11p	wireless access for the vehicular environment (WAVE)
IEEE 802.11s	mesh networking

Physical layer properties

802.11b, 802.11g, and 802.11n utilize the 2.400GHz-2.500GHz spectrum, also known as the ISM band. 802.11a and 802.11n use the more heavily regulated 4.915GHz-5.825GHz spectrum. These are commonly referred to as the "2.4GHz and 5GHz bands" on most sales literature. Each band is subdivided to channels of 22 MHz width except for the 802.11n that operates with a channel of 40MHz width.

If we take the example of the 2.4 GHz band, it is divided into 13 channels of 22 MHz each, beginning with channel 1 centered on 2.412 GHz. As shown in the Figure 15 below, that yields into only 3 non-overlapping channels.

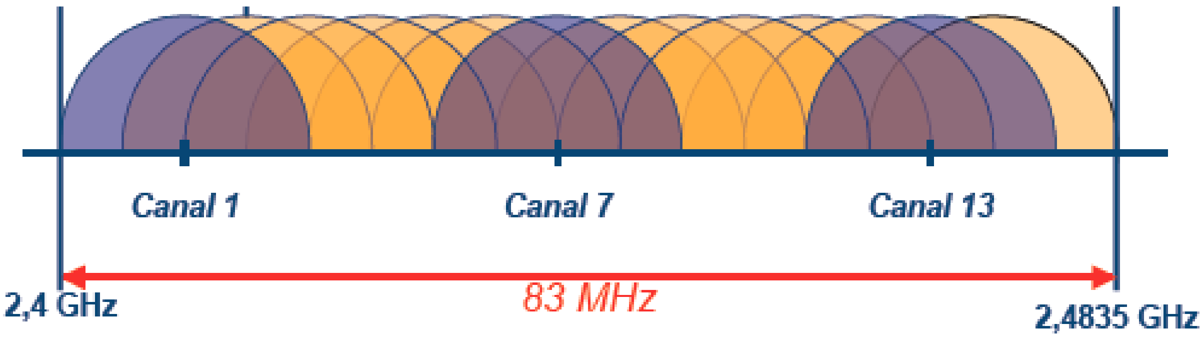


Figure 15. Channel allocation in IEEE 802.11 networks.

The used modulation schemes evolved with the standards evolution going from CCK for 5.5 and 11 Mbit/s and even DBPSK/DQPSK+DSSS for 1 and 2 Mbit/s in the 802.11b version to orthogonal frequency-division multiplexing (OFDM) with data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbit/s in the 802.11a/g versions.

Medium access control (MAC)

The IEEE standard specifies 3 techniques to handle the access to the shared medium in a distributed way.

- **DCF (Distributed Coordination Function)** ensures a random access to the wireless medium without any delay guarantee
- **PCF (Point Coordination Function)** uses a polling technique initiated by the access point to coordinate the access to the shared link. It allows priorities, (QoS) management, and delay control
- **HCF (Hybrid Coordination Function)** combines the two previous techniques

In practice, the DCF random access technique is the most spread today. Because this technique does not require any synchronization between participating nodes, it can be used in the standard infrastructure mode (with an access point) and ad-hoc/mesh mode. It is based on the carrier sense multiple access (CSMA) procedure that consists of listening on the shared medium for every sender willing to transmit. In case the medium is available for a period of time, the source can start transmitting, in contrast if the source detects activity on the medium, it differs its transmission. The CSMA technique is able to coordinate access to the wireless channel, however is unable to eliminate collisions in the case two emitters find the channel idle and start transmitting in the same time. For this, reason, the 802.11 DCF access includes a collision avoidance (CA) mechanisms that for every sent MAC frame requires an acknowledgement (ACK) from the receiver.

DCF also implements a set of timers and an exponential backoff to resolve the contention and collision issues. In fact, InterFrames (IF) are initiated before and after transmissions moreover a silence period exponentially distributed allows tie breaking and fairness after a collision and a transmission.

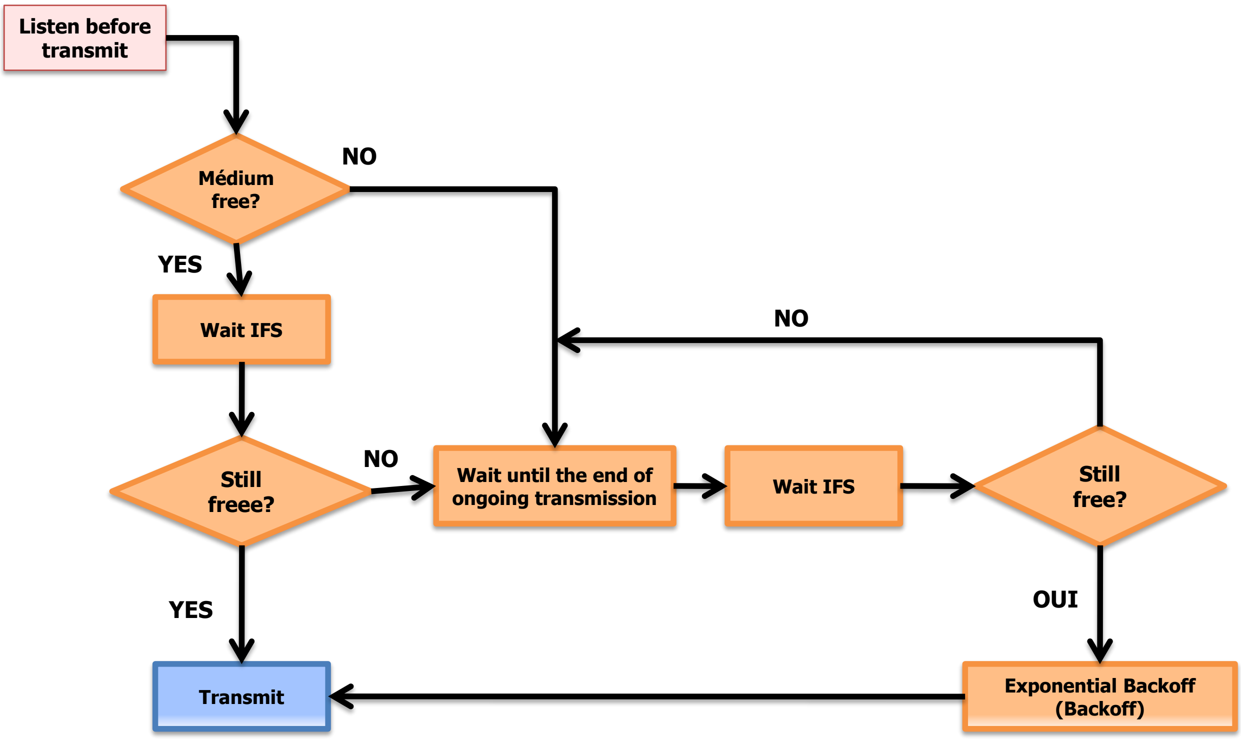


Figure 16. IEEE 802.11 MAC protocol.

More precisely, the DCF backoff enables conflicts resolution after a collision or before a transmission if the medium is detected busy. In fact, whenever the medium is seen occupied the source selects randomly a contention window distributed between [0 and CW] values. The randomness added in this process allows to reduce collision risks since two source nodes willing to transmit (or have already collided) have a low probability to select the same contention window size. In the latter case, i.e. after the first backoff selection the source is still unable to transmit successfully, The CW value is doubled increasing the possible values of the contention window. Therefore, the CW value increases exponentially with the number of unsuccessful tries hence the exponential backoff name associated to the mechanism.

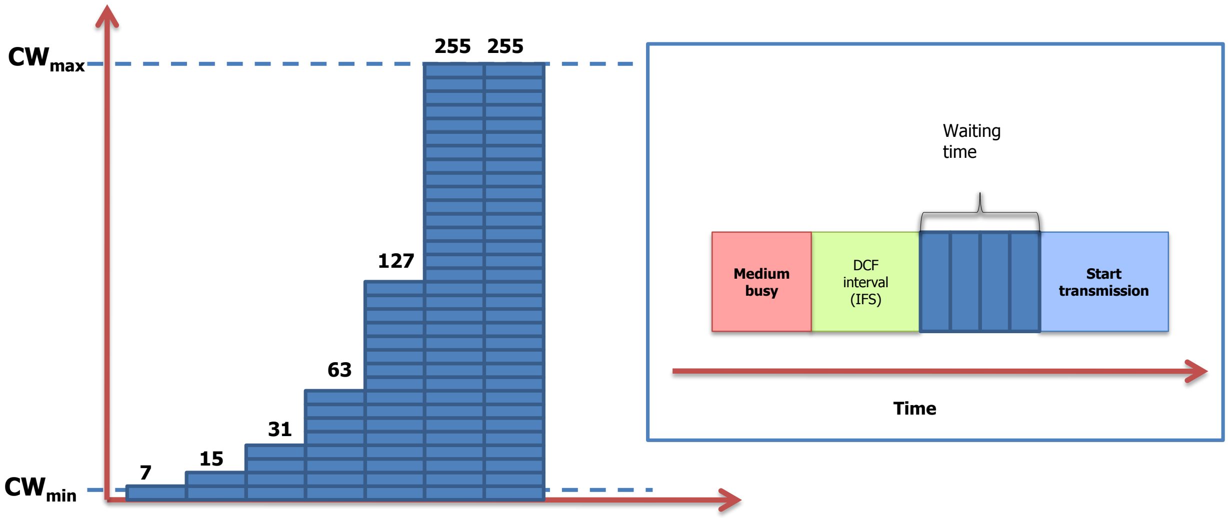


Figure 17. IEEE 802.11 DCF protocol.

The figure 17 above summarizes the DCF access technique however, even with this powerful backoff mechanism and the addition of MAC layer acknowledgements, collisions can still occur. Typically, such situations happen when the receiver is interfered by transmissions that cannot be sensed by the carrier sensing conducted by the sender. This problem is usually referred to as hidden node problem because emitters close to the receiver are hidden to the sender.

To overcome the hidden node problem the IEEE 802.11 protocols implement an **optional** virtual carrier sensing technique. This technique is based on a two messages handshake between the sender and the receiver before each transmission. More precisely, after listening on the medium, the source starts by sending a Request To Send frame (RTS) to the intended receiver that also contains the communication duration (Network Allocation Vector – NAV). If the receiver is able to receive the RTS and is available for the defined duration in the NAV, then it sends a Clear To Send frame (CTS) to the source that in which the NAV duration is also included. This CTS message informs all nodes close to the destination of the starting communication and its duration thus making them differ their transmissions for the defined NAV duration i.e. acting like a hidden node to the source. Only after this initial handshake, the usual DATA then ACK can normally take place.

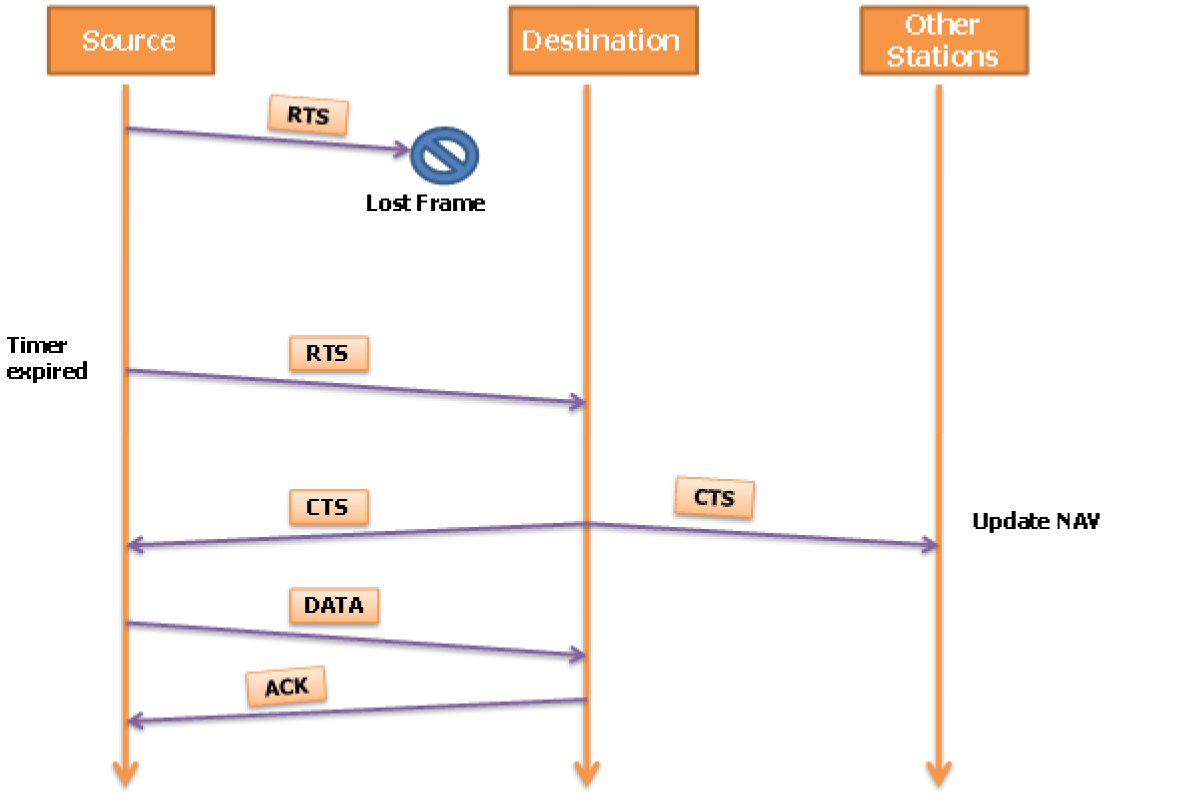


Figure 18. Virtual carrier sensing technique.

It is of a common knowledge that such random access techniques offer good performance when the network load is relatively low, i.e. with a limited number of senders. However, performance collapses when the number of users increases. As a result, with only 3 disjoint channels and a number of users constantly increasing, the IEEE 802.11 standards requires serious enhancements to be able to offer stable services to the increasing number of users.

3.2.2. Full duplex in 802.11 networks

As already highlighted, IEEE 802.11 protocols suffer from very poor performance with the increase of the number of users. Clearly, allowing simultaneous transmissions and receptions can enhance the observed performance.

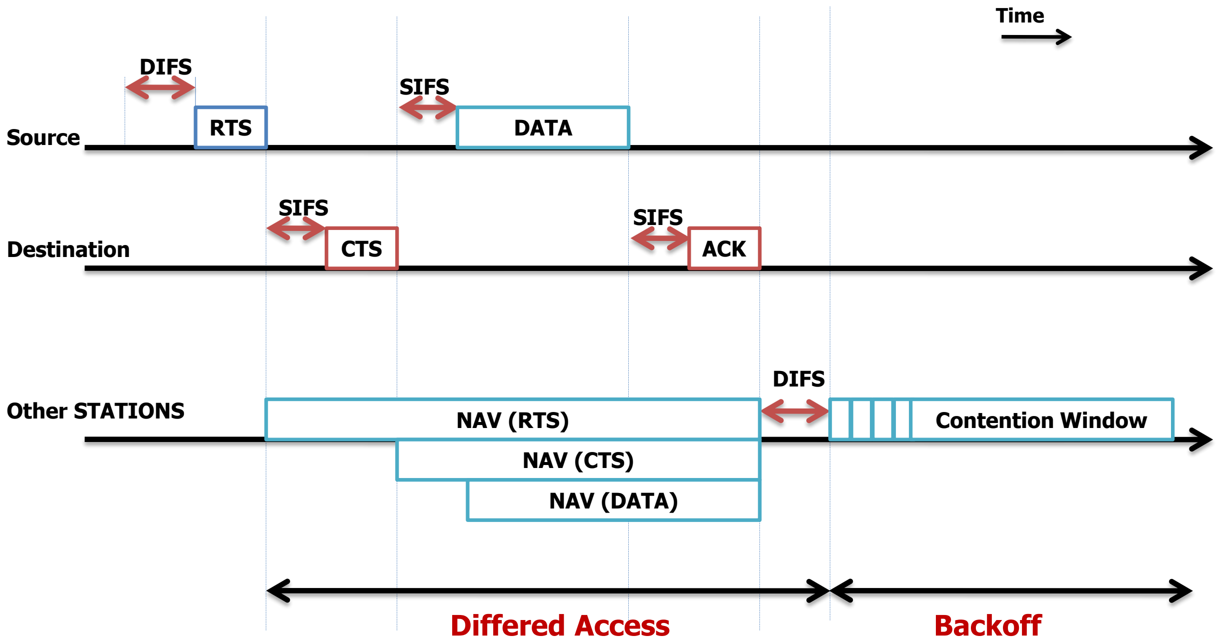


Figure 19. Access coordination in IEEE 802.11.

As shown in the figure 19 above, in order to be able to coordinate the access to the shared medium, the IEEE 802.11 standard introduces delays (IFS) and backoffs. These timers and delays reduce the usage of the channel capacities resulting in less throughputs for users.

Exploiting the ability to transmit and receive in the same time offers the following perspectives for the IEEE 802.11 standard:

- **Schedule transmissions to the sender while receiving its DATA**. In fact, this can be done when the destination has also information to send to the source. Usually, in such situations the 802.11 standard requires a backoff after the source transmissions (to ensure fairness) then a new normal carrier sensing, then if the channel is idle an RTS – CTS by the destination to send its DATA. However, in a full duplex mode the receiver can exploit the RTS – CTS exchange to inform the sender that a message will be sent to the source exactly in the same time. Moreover, the NAV initiated in the RTS can be exploited to dimension the size of the receiver message without affecting the timers and delays of the IEEE 802.11 protocols. Note here that the sender can acknowledge also the reception of full duplex data simultaneously with the receiver's ACK in full duplex.

The figure 20 below summarizes the full duplex communication in the 802.11 DCF RTS-CTS mode.

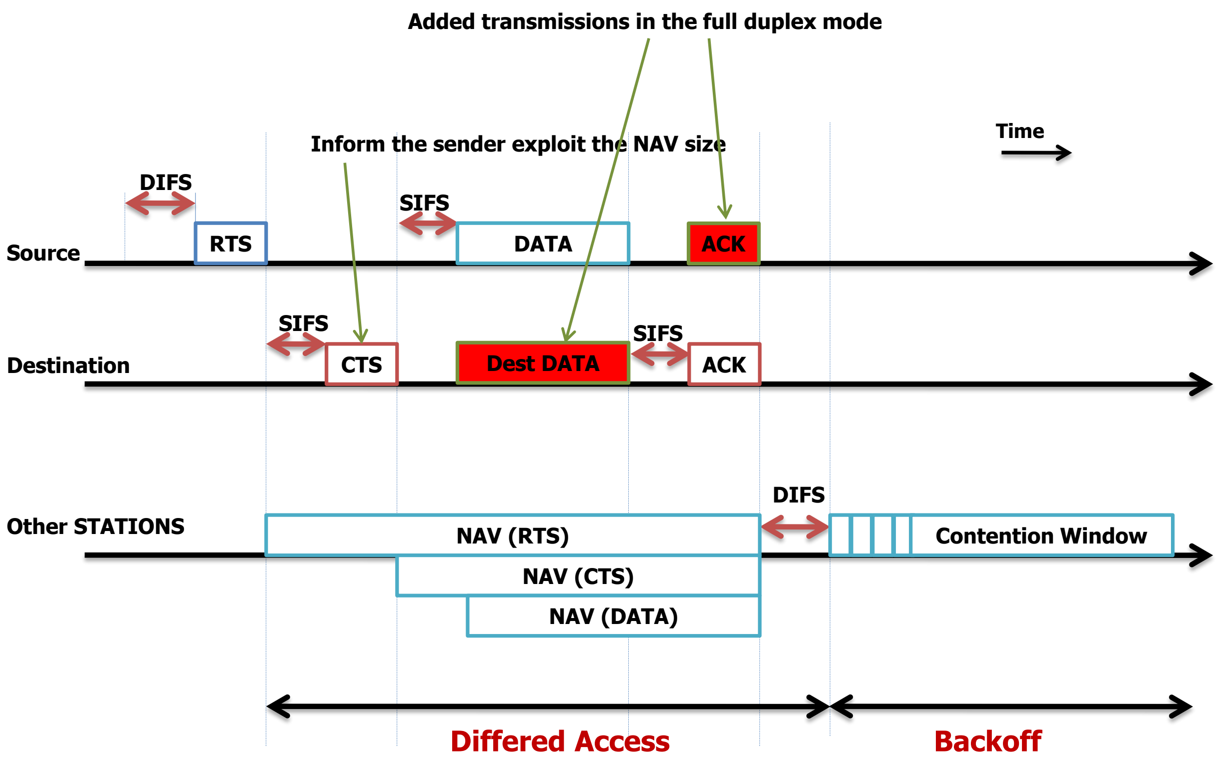


Figure 20. Full duplex communication in the 802.11 DCF RTS-CTS mode.

It is also important to notice that this full duplex communication scheme does not affect the fairness guaranteed by the IEEE 802.11 standard. Indeed, the scheduled receiver's transmissions do not affect in any case other stations backoffs or delays allowing them to transmit again normally at the end of the sender communication (plus contention window).
This full duplex version of the protocol allows considerable throughput gains. Practically, the achieved gains do not reach doubling the throughput, since the RTS – CTS handshake and other control messages introduced by the protocol remain unchanged. The estimated gain is proportional to the DATA messages size. Moreover, the solution is highly depending on the existence of receiver messages to be sent in the same time to the source. Nevertheless, the conducted changes do not add any new message in the protocol nor require any control information. In fact, all control exchanges are included within the RTS – CTS handshake and message sizes exploit the NAV information. Consequently the gains in terms of throughput achieved in this context are not affected by any other factors that might reduce their impact.
Clearly, in the case of the DCF mode without RTS – CTS handshake such signaling protocols need to be conceived, to determine the time and size of full duplex messages. In fact, the DUPLO protocol plans to propose management techniques and signaling protocol to exchange these control messages when needed.

3.3. Improvements to relay based networks

In the context of relay communications, conventional half-duplex radio based relay should be replaced by a full duplex radio based relay, which is a promising solution particularly for high-speed data services, increasing the spectral and energy efficiency in the local area (e.g., small cell networks). In a full duplex radio (FDR) based relay information is received and forwarded at the same time on the same frequency band. For example, it can be used in parallel with conventional half-duplex source and destination nodes, which do not necessarily support FDR functional capabilities on the source-relay and the relay-destination links, respectively. Instead, only a FDR relay node will receive and forward information at the same time on the same frequency band. In this case, same temporal and frequency resources between source-relay and relay-destination links can be used by the FDR relay and thus the end-to-end communications can be made by more efficient ways of accessing resources in time and frequency, compared with the half duplex relay systems. In DUPLO project emphasis is in the utilization of full-duplex transmissions in small cell systems and in public safety networks. Full-duplex relays may be considered as part of these two application areas of the full-duplex principle but it will not be studied as an independent topic in the project.

3.4. Improvements to public safety network operation

3.4.1. Background

With the emergence of the new generation of devices shall that shall equip public safety workers in order to assist their relief operations, the broadband capacity of PMR deployments becomes the issue. These devices are empowered with multi-interfaces and possess smartphone like capabilities. Therefore, exploiting these devices to offer new services is becoming an important requirement to public safety workers. However, the main challenge remains in the limited capacity of these today’s public safety systems

Blue force tracking (BFT) service aims at distributing to all participants in the relief operation the GPS coordinates of public safety workers. This service is achieved through a synchronized network where each worker broadcasts periodically its position that is then conveyed and shared with all other workers. Clearly, exploiting the advanced devices to distribute images, videos, and even voice recording from the scene can be of an extreme importance for rescue workers. These new type of information are even more important and pertinent when coupled to the exact geographical positions of participants (already offered by the BFT classical tracking).

Another service in public safety operation is the **Push To Talk (PTT).** The PTT allows asynchronous talkie walkie like communications between rescuers. It enables only voice point to multi-point communications with limited throughput. Clearly, adding to voice one directional communication, video and/or data services can help save lives in a rescue area.

The full duplex technology through the increase in system capacity and also the network coverage extension constitutes a promising perspective for public safety domain. We investigate through representative use cases the potential of this new technology. We also estimate the promised gains of full duplex systems in these particular scenarios.

3.4.2. Extending public safety infrastructure capacity and coverage

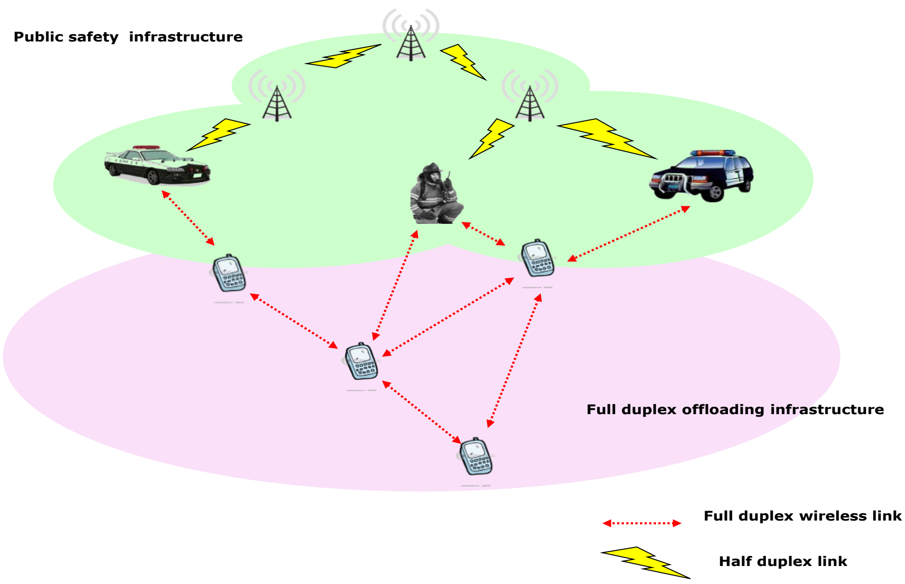


Figure 21. Coverage and capacity extension of public safety infrastructure.

As a key asset of mission critical communications, PMR narrow band technologies need to offer direct communications capabilities for terminals out of coverage of the infrastructure network. The key issue to operate in this device to device communication mode is the spectrum: what spectrum shall be devoted to such direct communications (Is it part of the infrastructure bandwidth, a separate part within the currently used spectrum for narrow band PMR systems or part of unlicensed spectrum?)

In the first scenario we investigate, the objective is to extend the coverage of existing infrastructure to cover more rescuers on the operation field. Existing solutions today, deploy new base stations of a high costs whenever the needs to accept more users in the system or even to cover longer distances arise.

Full-duplex systems present the advantage of extending the coverage of an existing infrastructure with limited costs. This offloading process only requires changes in the devices without any modification in the deployed physical infrastructure.

3.4.3. FDD based full-duplex systems

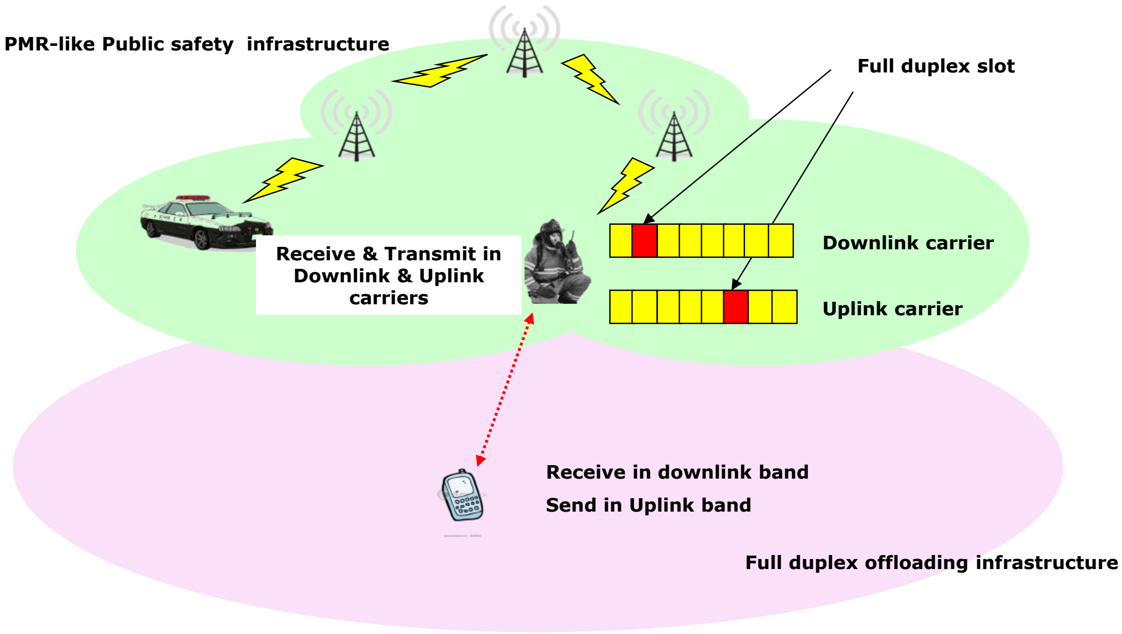


Figure 22. Full duplex in an FDD based PMR system.

We investigate first a PMR-like public safety system based on the FDD access for uplink and downlink. In such configurations, uplink and downlink operations take place on different set of frequency bands completely disjoint. As shown in Figure 22, a public safety terminal, equipped with the full-duplex technology, can exploit the downlink carrier to receive signals from the base station and also to communicate with other rescue workers in the same time. Similarly, in the uplink band a terminal transmits to the infrastructure and also receives from other rescuers also uplinking on the same channel. In summary, with full duplex systems, the normal functioning of a terminal that consists of transmitting in the uplink band and receive in the downlink band is kept unchanged. In fact, only nodes operating in full-duplex mode transmit and also receive in downlink and uplink.

3.4.4. TDD based full-duplex systems

In these systems Uplink and Downlink take place over the same bands but in different time slots. Similarly here, terminals can use the Downlink timeslots to transmit in downlink to their receiver, thus transmitting and receiving in the same time. Moreover, gains can be achieved when in Uplink time slots full-duplex terminals receive information from other nodes.

3.4.5. Backhauling Public safety infrastructure

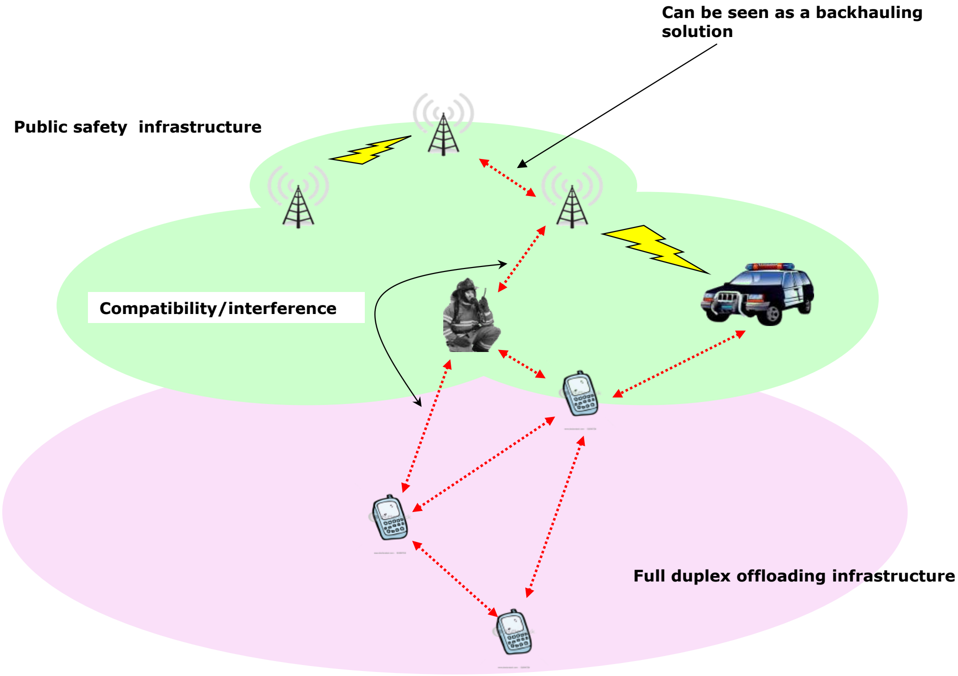


Figure 23. Backhauling with full-duplex.

Figure 23 shows the second use case where full-duplex can enhance the public safety systems. In this scenario, base stations can also use full-duplex technology to connect to other networks and potentially to the Internet. However, empowering base stations with this new technology requires important changes in the deployed infrastructure that can be of considerable costs. Moreover, the full-duplex coverage distance needs to be precisely characterized in order to investigate the feasibility of this scenario.

3.4.6. Performance metrics for public safety systems

- **Number of additional users in the system:** When planning public safety networks, estimating the number of users in the system is a key issue. The number of simultaneous communications is computed and the required provisioning is derived. Therefore if the maximum capacity is attained, any new arriving communication is simply dropped. However, in a public safety network dropping an arriving call is rarely tolerated. In fact, these networks are used in catastrophe situations and maximizing the number of communications is required. Accepting additional rescuers in the system can be achieved by extending the infrastructure thus deploying very costly equipment. For this reason, any new technology we propose for these networks shall be evaluated by looking at the number of additional users it allows in the PMR network.
- **System Capacity:** The additional capacity introduced in the network constitutes also an important metric to analyze. This capacity can either be exploited to accept more

users in the system or to allow new services between already existing services. Indeed, this latter case required by our customers today to convey new types of information such as videos, data, etc… cannot be evaluated by looking at the number of additional users in the network.

- **Number of full duplex receivers for a full duplex emitter:** Enabling full duplex communications is already hard to evaluate with point to point communications, however understanding the system behavior when point to multipoint communications are undergone is even more challenging. In fact, this communication pattern is frequently used in public safety operations with the BFT and PTT services. Consequently the number of receivers that can take advantage from a full duplex transmission enables us to better understand the system behavior in group communications.

- **Generated Interference to legacy users:** It looks clear that full-duplex technology brings advantage to traditional wireless systems. Nevertheless, in order to evaluate the offered advantages, it becomes necessary to clearly determine the impact of full duplex communications on non-full duplex devices. This metric allows measuring the backward compatibility with legacy communication systems. It is also of a major importance when planning a gradual deployment of a new technology.

- **System coverage extension in meters:** device to device communications allow the offloading of the deployed infrastructure and the extension of the coverage zone. As already precised, traditionally coverage extension requires new equipment with high costs. Therefore, estimating here the size of the new coverage zones in meters is an interesting metric to study.

- **Synchronization overhead in terms of generated control messages:** For optimal functioning of full duplex system an amount of control information need to be exchanged. This signaling traffic can help identify full-duplex slot, detect full-duplex users and legacy users etc. Estimating this additional traffic in the network is essential to characterize the performance of full-duplex systems.

3.4.7. Estimated Gains for public safety systems

Because full duplex systems allow to transmit and receive in the same time, it is expected that they enhance the performance of todays' wireless networks. We highlight below some envisaged gains from full duplex deployment in public safety networks. In practice, these estimations pushed us to investigate in depth this novel technology.

- **Grows with the number of full duplex users:** Intuitively, the more full-duplex users the system contains, the more the full duplex can be exploited. Therefore, one can easily see that the expected gains grow with the number of full duplex terminals in the network. However, this gain is bounded by the number of timeslots available for communication in the system. It will be also interesting to derive the lower bound in number of full duplex users in the system after which the gains become possible. In fact, a minimum number of full duplex users are needed to compensate the signalling overhead introduced by this new communication scheme

- **Throughput (capacity) gain**: As discussed earlier, the gain is directly impacted by the number of full duplex slot in the public safety infrastructure. Thus the gain in terms of total added capacity in the network is directly proportional to the number of full-duplex timeslots i.e full duplex users. More precisely, the added raw throughput can be estimated as follows: *n x bits/TS_duration*, where n is the number of full duplex time slots in the network, bits is the number of bits transmitted during a time slot duration (*TS_duration*). Note here, that the estimated capacity gain is expressed in bits/second.

- **Coordination and overhead estimation:** Clearly, all the expected gain cannot be properly accounted without considering the overhead added by this new technology. For this reason, achieved enhancements must also be evaluated with a particular consideration to the additional overhead. This overhead can take the form, of additional exchanged messages, dedicated time slots for signalling or any other type of control information.

4. DESIGN REQUIREMENTS AND CONSTRAINTS

4.1. Reference system characteristics

Since TDD is considered to be the likely choice for small cells in 3GPP it has been selected as a reference when defining requirements for full-duplex transceivers. Table 2 shows parameters for LTE femto and pico cells. These parameters are used as starting point when evaluating the feasibility of full-duplex transceivers in these environments. Full-duplex transceivers should offer the same range than TDD transceivers. However, the strong self-interference coupling from transmitter to node’s own receiver can limit the allowable transmit power resulting in decreased range unless efficient self-interference cancellation methods can be developed. It is likely transmit powers for full-duplex transceivers will be lower than those listed in table 2. Detailed analysis of radio parameters for full-duplex transmissions will be done in work package 2 of the DUPLO project. Self-interference cancellation requirements are evaluated in chapters 4.3 and 4.4 using the parameters from table 2. In addition to deterministic transmit signal the noise generated in transmitter must be taken into account when assessing the needed for self-interference cancellation. Transmitter induced noise and is influence on the full-duplex transceiver is treated in chapter 4.2.

Table 2. Parameters for LTE femto and pico cells.

	Femto-cell	**Pico-cell**
Environment	Indoor, single room	Outdoor, isolated
Maximum transmit power of base station	20 dBm	30 dBm
Maximum transmit power for UE	23 dBm	23 dBm
Communication range	0 – 50 m	10 – 200 m
Path loss model	Dual strip model (UE and BS in the same building): $L = 38.46 + 20\log_{10}(R) + 0.7R + 20\log_{10}(F_{GHz}/2)$	$PL_{LOS}=103.8+20.9\log10(R_{km})+20\log_{10}(F_{GHz}/2)$
Center frequency	2 GHz	2 GHz
Bandwidth	10 – 100 MHz	10 – 100 MHz
EVM requirement	22 dBc (64-QAM)	22 dBc (64-QAM)

Table 3 lists parameters for the legacy public safety system based on TETRA standard. As can be seen from the table the transmission powers of the TETRA system are considerably higher than in LTE small cell specifications. This means that the for public safety systems the self-interference cancellation at antenna and RF front end level is even more critical than in small cell environment.

Table 3. Parameters for public safety systems.

	TETRA direct mode	**TETRA**
Maximum transmit power of base station	--	44 dBm
Maximum transmit power for UE	40 dBm	40 dBm
Communication range	1 km	4 km
Path loss model	$69.55 + 26.16\log_{10}(f_c) - 13.82\log_{10}(h_b) - (1.1\log_{10}(f_c) - 0.7)h_m + (1.56\log_{10}(f_c) - 0.8) + (44.9 - 6.55\log_{10}(h_b))\log_{10}(R) - 2(\log_{10}(f_c/128))^2 - 5.4$ [dB] h_b = BS antenna height, h_m = UE antenna height, f_c = frequency (MHz), R = distance.	
Bandwidth	25 kHz/channel	25 kHz/channel
EVM requirement	Peak 0.3 per symbol (PI/4 DQPSK)	Peak 0.3 per symbol (PI/4 DQPSK)

4.2. Impact of transmitter EVM on a full-duplex link budget

As discussed before, the signal-to-interferer-and-noise ratio (SINR) referred to the input of the receiver is an important metric to determine the range of a wireless link. In a full-duplex link budget, the limiting component of the SINR is expected to be the strong self-interferer. This self-interferer again consists of the transmitted signal and various less deterministic components, often grouped together in one number, the Error Vector Magnitude (EVM). This section discusses the expected impact of EVM on full-duplex communication.

4.2.1. Definition of EVM

EVM is defined as the RMS magnitude of the error vector between the received constellation points and the corresponding ideal constellation points, see figure 24.

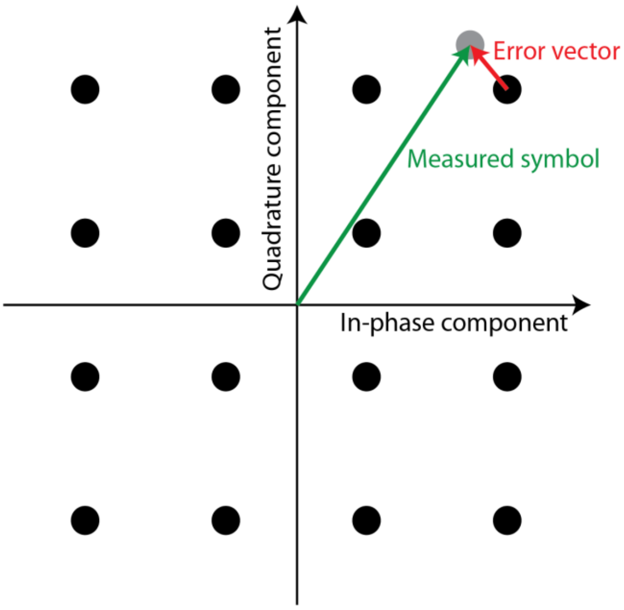


Figure 24. The error vector depicted in a 16-QAM constellation.

As such, EVM is a single number to describe the degradation of the transmitted signal due to several transmitter impairments, such as phase noise, I/Q imbalance, amplitude distortion, phase distortion and thermal noise.

The exact definition of EVM differs slightly depending on the chosen standard: in defining EVM, it is assumed that the receiver is able to correct for a number of transmitter and channel impairments, which differ between standards. For instance, in single-carrier systems, the receiver often performs matched filtering, phase and amplitude equalization before measuring EVM. In OFDM systems, the receiver performs the FFT and equalization for each subcarrier before measuring EVM.

An EVM given in dBc can be converted to a percentage by means of:

$$\mathrm{EVM}[\%] = 100 \cdot 10^{(\mathrm{EVM[dBc]}/20)}$$

This is because the EVM in dBc is a power ratio, and the EVM in percentage is the magnitude error of a voltage vector. Example: -40 dBc of EVM equals 1.0 %.

4.2.2. Impact of EVM on full-duplex

Assume two full-duplex nodes, a "local" node and a "remote" node. In full-duplex, both of their receivers are affected by self-interference. E.g. the self-interference at the local node consists of the 'clean' self-interferer from the local TX and, usually tens of dB below it, the EVM of the local TX.

Viewed from the antenna inward, one or more stages will provide self-interference cancellation at RF, which cancels both the clean interferer and the transmitted EVM equally. Further down the chain, for instance in the digital baseband section, there may be a stage that has no knowledge of transmitter EVM, and is only capable of further cancelling the clean self-interferer. If the clean interferer is sufficiently suppressed, the remaining dominant self-interference is the EVM. Therefore, the EVM of the local TX may effectively raise the noise floor at the local RX, reducing its sensitivity. This situation is qualitatively depicted in figure 25. Both nodes transmit a signal affected by EVM at equal powers. Within the local node, self-interference cancellation at RF applies to both the clean signal and its EVM. Subsequent cancellation (e.g. digital) applies only to the clean interferer. As a result, the receiver sensitivity is degraded and the tolerable path loss is reduced, resulting in a shorter link distance.

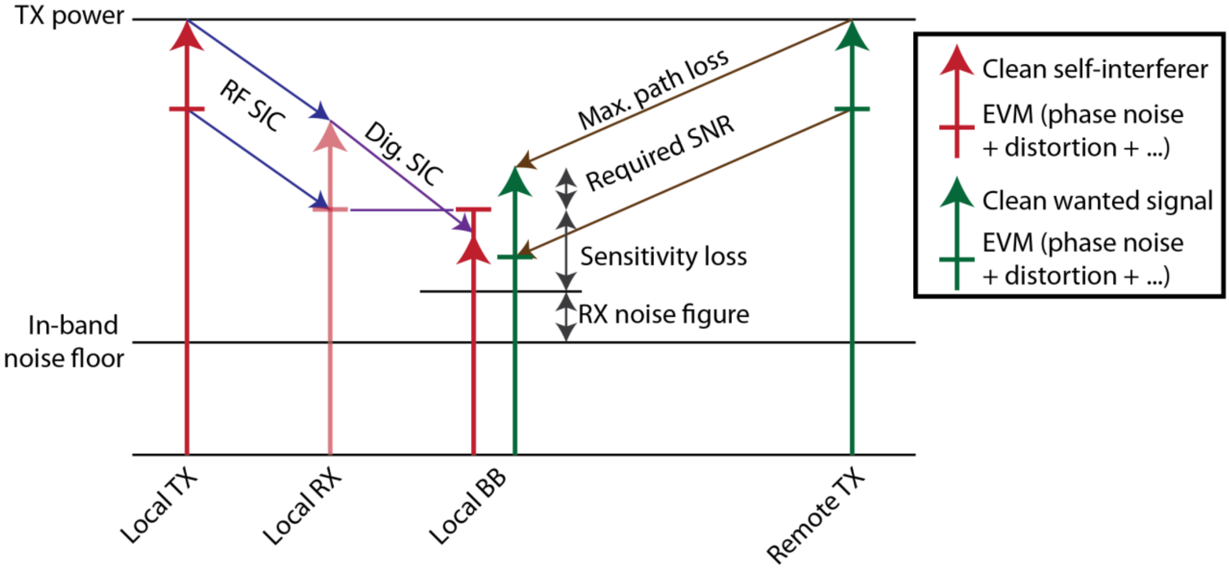


Figure 25. Degradation of the receiver sensitivity due to the EVM-content of the self-interferer.

For short link distances, the channel capacity is not limited by this reduced receiver sensitivity, since there is plenty of signal received, but by the EVM performance of the local TX. So for short distances, a better EVM is equally beneficial to increase the channel capacity in half-duplex and full-duplex. For long link distances, better EVM performance helps full-duplex to be competitive to half-duplex.

The EVM issue can be tackled in different ways, for instance:

- Reduce the amount of EVM at the source (e.g. implement a clean transmitter)
- Increase the amount of self-interference cancellation that applies to both the clean interferer and the EVM.

4.2.3. EVM in a full-duplex context

Note that for full-duplex, the in-band floor of 'noisy' components is not strictly spoken equal to EVM. As discussed, EVM is measured after the receiver corrects for several transmitter impairments. The "digital" self-interference cancellation stage cannot correct for any such transmitter impairments, since this may distort the weak received signal. It can, for instance, merely subtract a scaled version of the transmitted signal. What remains is a floor of noisy components that is strongly related to the EVM, but not exactly the same. This is a topic of further investigation, and for the time being, actual EVM figures are used to approximate the transmitter behavior for full-duplex.

4.2.4. Tackling EVM at the source: review of transmitter literature

To investigate the feasibility of reducing the EVM at the source, a short literature study was conducted. For reference, Table 4 shows typical physical layer requirements for the transmitter in different wireless standards. For standards that support multiple modulation schemes, the most challenging scheme was chosen.

Table 4: Requirements set by different wireless standards on the transmitter

		GSM/EDGE	WCDMA	WLAN (g)	LTE
Band center (typ.)	MHz	1800	1950	2450	1940
Signal Bandwidth	MHz	0,2	5	16.6	20
Modulation	-	GMSK/8-PSK	HPSK	64-QAM OFDM	64-QAM OFDM
Peak-to-Average ratio	dB	0/4	3,5	10	8
Power Control Range	dB	30	74	-	74
EVM [%]	%	9	17,5	5,6	8
ACPR @ offset freq	dB	-30	-33	-28	-40
ACPR offset frequency	MHz	0,2	5	20	20
RX Noise	dBc/Hz	-162	-160	-	-160

Existing CMOS integrated transmit modulators can be roughly divided into two groups based on their output power: modulators with roughly 0-6 dBm of output power, that are intended to be followed by an external PA to form a practical transmitter, and modulators with roughly > 10 dBm of output power that can drive an antenna or duplexer directly.

Note that for full-duplex demonstration purposes over short distances, the power levels generated by a pre-PA modulator may be sufficient (i.e. no integrated or external PA may be necessary).

Both pre-PA and fully integrated transmitters were investigated. The separation between the two types can be motivated by considering how much power can be easily output into a 50 ohm environment from a typical CMOS IC. Suppose a 1 V supply is available, and a differential output voltage is generated. Then a reasonable output swing that can be linearly supplied into a 50 ohm load is about 1Vp-p. This is about +4 dBm. To achieve higher power levels without an external PA, on-chip or off-chip transformers or additional supply voltage domains are usually required.

In conclusion of this literature study, both pre-PA and fully integrated transmit modulators show that EVM figures in the order of 1% to 2% are state-of-the-art (i.e. -40 to -34 dBc).

4.3. Self interference cancellation requirements from information theory

A preliminary study has been taken to compare a full-duplex link with the corresponding half-duplex link in order to give intuitive understanding about the minimum requirement of the self-interference cancellation (SIC) capability in the full-duplex transceiver. In this study, the non-linearity effect namely error vector magnitude (EVM) due to imperfection implementations is modeled as Gaussian noise added to the original signal at the transmitter. The average power of the EVM noise is proportional to the average power of the original signal. This approximation partially follows the non-linearity analysis shown in [39]. As a benchmark, the 'optimal' half-duplex scheme that uses adaptive downlink and uplink bandwidth allocation is selected. The assumed full-duplex transceiver has a simple three-stage self-interference cancellation functionality. The transmitted signal is first attenuated by the antenna isolation between the own transmit and receive antenna(s). After that, it arrives at the own receive RF front-end as the self-interference, which is further suppressed by a RF canceller before it is transformed into baseband signal. It is assumed that the self-interference caused by both the original signal and the EVM noise can be equally suppressed by the antenna isolation and the RF canceller. The third stage is a self-interference canceller at digital baseband. In this stage, only the self-interference caused by the original signal can be estimated and subtracted, while no self-interference caused by the EVM noise can be cancelled in our assumption.

Different local communication environments have been investigated in the preliminary study. We considered the flat fading channel that follows free-space path loss model. Using Shannon link capacity formula, the rate region of the full-duplex link with different SIC capability was compared with the rate region of the half-duplex link. In Table 5, we list the required SIC capabilities before digital baseband processing in order to achieve certain level of maximum sum rate advantage. In all computations, it was assumed that the digital baseband canceller could suppress 30 dB self-interference caused by the original signal.

Table 5. Full-duplex gain under different SIC capability – free-space path loss model ('X' means that the target cannot be reached)

Bandwidth (MHz)	Max Tx Power (dBm)	Distance (m)	EVM noise level (dBc)	Antenna Gain (Node1, Node 2) (dBi)	Noise figure (Node1, Node 2) (dBi)	SIC requirement before BB to reach N% per cent of maximum sum-rate of half-duplex (dB)		
						≈100%	≈150%	≈190%
20	20	5	-30	(0, 0)	(9, 9)	-43	-51	-68
20	20	10	-30	(0, 0)	(9, 9)	-50	-57	-78
20	20	50	-30	(0, 0)	(9, 9)	-63	-71	X
20	20	5	-40	(0, 0)	(9, 9)	-46	-56	-78
20	20	10	-40	(0, 0)	(9, 9)	-52	-62	-81
20	20	50	-40	(0, 0)	(9, 9)	-64	-74	X

Besides the free space model, we also investigated small cell environments defined by 3GPP LTE standards for indoor femto and outdoor pico base stations. A standalone femto-cell and pico-cell were considered in the analysis. The results have been summarized in tables 6 and 7.

Table 6. Full-duplex gain under different SIC capability - indoor femto-cell single-room path-loss model ('X' means that the target cannot be reached)

Bandwidth (MHz)	Max Tx Power (dBm)	Distance (m)	EVM noise level (dBc)	Antenna Gain (Node1, Node 2) (dBi)	Noise figure (Node1, Node 2) (dBi)	SIC requirement before BB to reach N% per cent of maximum sum-rate of half-duplex (dB)		
						≈100%	≈150%	≈190%
20	20	5	-30	(0, 0)	(9, 9)	-47	-55	-70
20	20	10	-30	(0, 0)	(9, 9)	-56	-64	-84
20	20	5	-40	(0, 0)	(9, 9)	-49	-59	-75
20	20	10	-40	(0, 0)	(9, 9)	-58	-69	X

Table 7. Full-duplex gain under different SIC capability - outdoor standalone pico-cell path-loss model ('X' means that the target cannot be reached)

Bandwidth (MHz)	Max Tx Power (dBm)	Distance (m)	EVM noise level (dBc)	Antenna Gain (Node1, Node 2) (dBi)	Noise figure (Node1, Node 2) (dBi)	SIC requirement before BB to reach N% per cent of maximum sum-rate of half-duplex (dB)		
						≈100%	≈150%	≈190%
20	20	10	-30	(5, 0)	(13, 9)	-52	-61	X
20	20	50	-30	(5, 0)	(13, 9)	-66	-75	X
20	20	10	-40	(5, 0)	(13, 9)	-55	-65	X
20	20	50	-40	(5, 0)	(13, 9)	-67	-77	X

By observing all results, a rough conclusion can be drawn:

In order to reach the same performance as that of the half-duplex link, roughly 43 ~ 67 dB SIC capability before baseband processing is required when the communication range varies from 5 ~ 50 meters and the EVM noise level is between -30 and -40 dBc. Accordingly, the overall SIC requirement is 73 ~ 97 dB.

In order to get 50% gain over the half-duplex link, the overall SIC requirement is increased to 81 ~ 107 dB, while the number of the cancellation capability before baseband processing is 51 ~ 77 dB.

For the investigated outdoor pico-cell environment, the full-duplex link could only achieve less than 90% gain over the half-duplex link. It may be a big challenge to achieve very high full-duplex gain in this scenario.

The above results were obtained with 20 MHz bandwidth at 2.4 GHz carrier frequency. For 10 MHz bandwidth, the results may not be changed too much, because reducing the bandwidth into half of the original bandwidth just reduces about 3 dB of equivalent noise.

4.4. Self interference cancellation requirements from communication engineering

Communication systems are designed to satisfy requirements set in standards. For example, assume that the requirement is to have the un-coded bit-error-rate (BER) of 10^{-3}. Table 8 presents values for signal-to-noise ratio that fulfil this requirement in AWGN channel. If full-duplex transceiver is able to suppress the self-interference to level that gives the BER of 10^{-3} then the introduction of the full duplex will double the achievable data rate constrained by the standard (modulation).

Table 8. SNR requirements to achieve 10^{-3} BER with different modulations:

Modulation	Eb/N0 [dB]	SNR/modulation symbol[dB]
BPSK	7	7
4-QAM	7	10
16-QAM	10.5	16.5
64-QAM	14.8	22.6

For an initial analysis it is assumed that the interference is Gaussian noise and the transmit power of the nodes is 20 dBm. Assuming path loss model of a pico cell from Table 2 the path loss is 63.6 dB for 10 meter link distance and 78.2 dB for 50 m distance. The noise level caused by the non-ideal operation of the transmitter (EVM noise) is assumed to be -30 dBc. Since the EVM noise is much stronger than the thermal noise, the thermal noise can be ignored in these calculations. With these figures the signal-to-noise-and-interference ratio (SINR) for 10 meter link is -63.6 dB and -78.2 dB for the 50 meter link distance. Based on these values the self-interference cancellation requirements to attain SNR values of the table 8 are presented in table 9

Table 9. Self-interference cancellation requirement:

Modulation	10 m	50 m
BPSK	70.6 dB	85.2 dB
4-QAM	73.6 dB	88.2 dB
16-QAM	80.1 dB	94.7 dB
64-QAM	86.2 dB	100.8 dB

In previous chapter it was concluded that in order to improve information theoretic channel capacity by 50% the self-interference should be attenuated by 81 – 107 dB. However, values in table 9 indicate that it is possible to increase the throughput of practical systems with lower self-interference capability than what is defined by information theoretic analysis.

4.5. Identification of different form factors

The fundamental challenge in full-duplex wireless communication systems is reducing the self-interference. As a consequence, full-duplex transceivers base their performance on the combination of different analog and digital self-interference cancellation techniques, in order to reduce the portion of its own transmission which interferes in the receiver.

In general, some of these cancellation techniques have a strong impact on the size of the wireless device and could determine the degree of integration of full-duplex transceiver. For instance, antenna placement is considered as a cancellation technique in analog domain. This technique uses the fact that the distance between transmit and receive antennas naturally reduces the self-interference due to signal attenuation. However, the distance between both antennas must be large enough in order to achieve an acceptable value of self-cancellation. Figure 26 illustrates the effect of increasing the distance between transmit and receive antennas on the self-interference attenuation. The results showed on this graph have been obtained simulating both antennas with variable distance between them. The antennas consist of omni-directional antennas models which radiate uniform field in the horizontal plane.

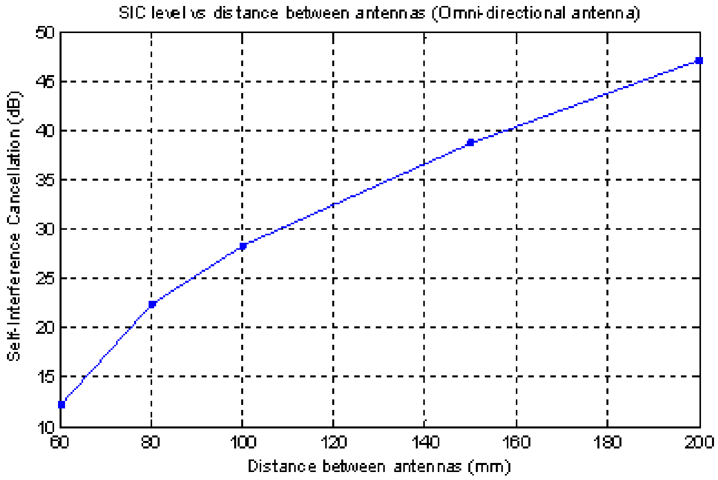


Figure 26. Self-interference cancellation considering different distances between antennas at 2.4 GHz.

As can be seen on Figure 26, it is necessary to have distances larger than 160 mm to obtain an interference reduction of 40 dB. This fact makes this technique unfeasible when small-form factors are required.

As aforementioned in previous sections, full-duplex transmission has several potential applications in wireless communication systems. Over last decades, due to both technological advance and fierce competition, a large variety of mobile devices have been introduced in the marketplace to satisfy the necessities of these applications. Current mobile devices offer a diverse set of form factors to cater the preferences and requirements of a large set of users. In this section different form factors considering different scenarios has been identified. Table below shows some reference values for these form-factors:

Table 10. Form factors for full-duplex communications

BASE STATIONS	**Femto Base Station form factor**	236 x 160 x 76 mm
	Pico Base Station form factor	426 x 336 x 128 mm
	TETRA Base Station form factor	55 x 143 x 57 cm
ACCESS POINTS / USER EQUIPMENTS	**Netbook**	285 x 202 x 27.4 mm
	Tablet PC	241.2 x 185.7 x 8.8 mm
	SmartPhone	123.8 x 58.6 x 7.6 mm
	PDA	132 x 66 x 23 mm

The aims of defining different applicable form factors are:

- To identify the feasibility of each form-factor from the point of view of demonstrator.
- To employ these form factors as inputs of work package 2. Each of the form factors will have an impact on the transceiver size and this could imply the rejection of some analog cancellation techniques which not adapt to the form-factor requirements. Moreover, in the specific case of DUPLO antenna design, the form factor will be used also to analyse the impact of the wireless device on the radiation pattern and on the performance of the antenna.

A huge benefit can be gained by using antenna techniques for larger form-factors, since robust, wideband cancellation may be achieved [5,6], but system size constraints limit its applicability across form-factors.

In principle, devices of all form factors should have full-duplex support, especially since connectivity between any devices is desired from a user perspective. However, given the form factor, antenna-based self-interference cancellation techniques may not be permitted, nor may there be available space to implement multiple or larger-sized antennas without compromising implementation of all system capabilities end-users are accustomed to.

The most obvious example that would be problematic from the listed devices in table 10 is the smart phone, the size of which is determined mainly by the screen and battery requirements for a given handset, leading to size constraints. E.g. across different handsets, screen size may vary from 2” to 5.5”, or even larger. Furthermore, the space reserved for electronics is limited and integration of any component is paramount for practical implementation of mass-producible devices, where cost reductions are key. Finally, section 1.2 already clearly illustrated the benefit full-duplex could offer for devices with a smaller form-factor, since a large portion of the total data traffic is coming from handheld devices.

When the time is right to start standardizing full-duplex, such ‘5G’ or ‘next-gen WiFi’ standards have to co-exist with many other wireless standards, and the transceiver will be re-used to suit multiple different standards and operate among many different frequency bands. As a result, it is desired that a full-duplex solution with self-interference cancellation capabilities is compatible with half-duplex, e.g. with frequency-division duplexing schemes.

For the above-mentioned reasons, this project studies and implements novel techniques to advance antenna-cancellation state-of-the-art, so that large form-factor devices may gain its benefits, while also exploring disruptive techniques for solutions that may offer full-duplex support for small, handheld devices.

4.6. Proof-of-concept initial set-up and requirements

The project aims to implement a proof-of-concept hardware demonstrator to verify that the solutions developed in the project can be compiled together as a complete and working full-duplex transceiver solution which can operate at least in a subset of system scenarios discussed in chapter 3.

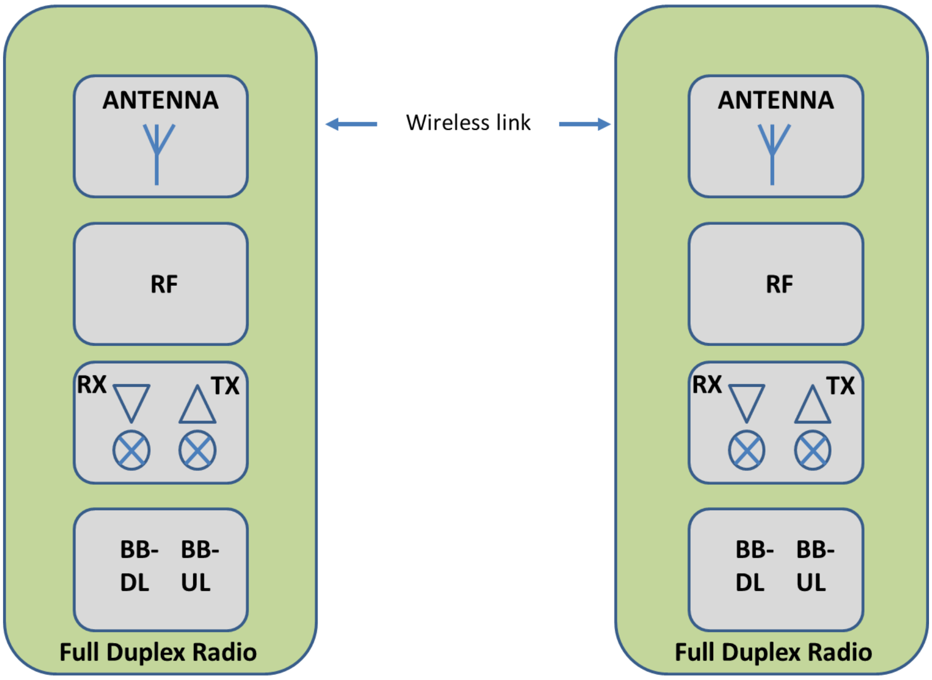


Figure 27. Proof-of-concept initial set-up

The set-up for the proof-of-concept is shown in Figure 27. Indicative system and equipment specifications for the proof-of-concept setup are given in Table 11.

Table 11. Initial requirements for the proof-of-concept.

Feature		**Specification**
System Level	**Scenario**	LTE femto cell
	Initial system set-up	Wireless point-to-point connection between two full-duplex transceivers. Transmission distance: 1m – 5m. Traffic model: full-buffer data stream in both transmission directions. Wireless channel: realistic dynamic indoor environment with e.g. moving objects.
	Radio transmission characteristics	Carrier frequency: 2.4 GHz [1)] Transmitted signal bandwidth: 10 MHz or 20 MHz [2)] Transmitted signal power level: ≤ 20 dBm [3)] note 1: 2.4 GHz ISM band note 2: signal bandwidth selected to represent typical LTE signal transmission bandwidth note 3: maximum Tx power. Smaller Tx power may

		be used with practical demonstrations.
	Device types	Access point and UE device; differentiating in form factor.
Equipment level	**Full-duplex transceiver performance targets**	Demonstrate robust and automatically tuned full-duplex operation over varying environmental conditions. Measure and visualize both the full-duplex system performance and the full-duplex performance of specific components. Possible performance metrics are: self-interference cancellation, data throughput and error-vector magnitude.

5. SUMMARY AND CONCLUSIONS

The fundamental feature of full-duplex communications is the possibility to transmit and receive simultaneously on the same carrier frequency. This feature offers the potential for sustainable wireless communication by developing new full-duplex systems and radio equipment. This sustainability mainly reflects in supporting the vast increase of data traffic with limited resources, the mobility and portability of the communication devices and the variation of the consumed data traffic. The full-duplex concept has already been described in literature, but these publications lack to solve the critical issues at system and device level. The DUPLO project focuses on the study and design of full-duplex radios and systems, by considering realistic conditions, scenarios and constraints. The DUPLO solutions will be validated in an integrated demonstrator, illustrating the performance of full-duplex communication.

This document reports the results of the work performed in WP1, entitled ‘Scenario and requirements’. First, the full-duplex concept is described and motivated in frame of the future evolution of wireless networks and data traffic. Second, the potential network topologies (links and systems) are discussed where full-duplex is beneficial. Then, different scenarios are introduced based on the relevant network topologies, and further, the practical design requirements, constraints and technical specifications are identified for the small-cell LTE scenario. Finally, preliminary directions are described to integrate the project solutions in an integrated demonstrator that will be used for run-time validation.

The full-duplex concept is very promising to sustain the evolution of data traffic and spectral usage. At physical layer, the theoretical gain of full-duplex equals to doubling the capacity or spectral efficiency in a point-to-point link case compared to half-duplex (e.g., either time division duplexing or frequency division duplexing), assuming perfect self-interference cancellation capability. Thus, achievable throughput (link or system level throughput) is one performance metric with full-duplex impact. Other performance metrics are related to the self-interference cancellation, but also network related such as end-to-end delay, packet loss ratio, and average energy expended per transmitted bit or packet. Full-duplex has also impact on protocol design as discussed in chapter 2.

The evolution of future networks evolves towards small-cells, ad-hoc and mesh networks, with users traveling across cells and consuming varying amounts of data. Other networks such as UE relay and public safety networks are also considered as potential application areas for full-duplex communications. For all these networks, different scenarios to utilize and exploit the full-duplex principle are identified and motivated in chapter 3:

- The primary target for using full-duplex technology in LTE small cell operation environment is to improve system spectral efficiency through using the same radio resources for simultaneous transmission and reception in different nodes of the radio system. Small cell system supporting multiple simultaneous connections between the base station and user devices can benefit from the fundamental advantage of full duplex communications in multiple ways, e.g., using full-duplex communications for each base station – device connection separately, or using full-duplex communications principle in the base station to enable simultaneous transmission to one user device and reception from another device. Another mechanism to benefit from full-duplex in small cell operation environment is the potential full-duplex transceiver ability to listen the radio channel or receive link or system control information simultaneously while transmitting data. This could potentially provide improvements in system and individual link performance. Achievable system level gain of full-duplex communications (over conventional half-duplex system, e.g., LTE TDD system) is expected to be between 0% and 100 %, depending on various system parameters (e.g., traffic load between uplink and downlink, system operation environment, etc.).

- Full-duplex technology could be utilized to improve system performance also in IEEE802.11 technology based networks, including infrastructure based operation, ad-hoc and mesh networks. The basic mechanisms to benefit from full-duplex communications and foreseen achievable system level gains are similar to LTE small cell systems. However, the channel access and radio resource management solutions are different in IEEE802.11 technology based systems, which enables also new ways of using full-duplex to improve system performance. For example, full-duplex operation can mitigate the hidden node problem in IEEE802.11 technology based systems.
- Another potential system application for full-duplex technology is device to device communications and use of devices as relaying nodes in public safety networks. The foreseen benefits of full-duplex communications in this scenario are improved system capacity and coverage.

For a reliable wireless full-duplex communication, the self-interference cancellation requirement between the radio transmitter and its own receiver is extremely challenging. This cancellation should prevent that the transmitted signal, which is very powerful, masks the signal of interest coming from distant source in its own receiver. During the project, a coordinated design over the different building blocks (antennas, analog circuitry and digital signal processing) is crucial to obtain a constructive behavior with respect to the self-interference cancellation. The selected system application scenarios set requirements and constraints to the full-duplex transceiver. For example, in small area wireless communication systems, the power level difference between the transmitted signal and the received signal from distant source is relatively small enabling potential use of full-duplex transceivers with small form factor. In some other scenarios, e.g., communications between base stations, full-duplex transceivers may have more form-factor capabilities, enabling also use of large communication distances.

LTE is considered as the most likely choice for small cell technology enhancements in future 3GPP specification releases, and is therefore selected as the reference for defining requirements for full-duplex systems and deriving initial transceiver design requirements, constraints and high-level technical specifications. Initial information theory based link level performance analysis indicates that the full-duplex transceiver should have total self-interference cancellation capability of 81 to 107 dB in order to be able to provide 50 % gain over half-duplex link with 5 and 50 meter link distances, respectively. Complementary analysis from communication engineering point of view indicates that self-interference cancellation requirement is 70.6 dB to 86.2 dB to achieve bit error rate of 10^{-3} with 10 meter link distance using BPSK and 64-QAM modulations, respectively. Corresponding results with 50 meter distance indicate requirement of 85.2 dB to 100.8 dB using BPSK and 64-QAM modulations, respectively. Initial results indicate that very powerful self-interference cancellation is thus needed for the full-duplex wireless transceiver.

Transmitter noise induced problem in full-duplex receiver is an important observation from the conducted DUPLO project work. Transmitter noise is caused by imperfections in the practical transceiver (such as phase noise, I/Q imbalance, non-linearity in the power amplifier). The measure of the impairment, error vector magnitude (EVM), is defined as RMS magnitude of the error vector between the received signal constellation points and the corresponding ideal constellation points. Results indicate that EVM limits the full-duplex (and half-duplex) system performance for short transmission distances. EVM impact to full-duplex system performance can be alleviated either by implementing better transmitters (with more clean transmit signal) or improving self-interference cancellation that applies to both the clean interferer and the EVM component.

To validate applicability of the full-duplex principle on different devices (base-station, tablets, smartphones, M2M), different form-factors will be considered throughout the project. It is expected that each form factor will provide its specific opportunities and drawbacks, and that several full-duplex solutions will be applicable on all form-factors.

The project will implement a proof-of-concept hardware demonstrator to validate that the solutions developed in the project can be compiled together as a complete and working full-duplex transceiver solution, operational on a subset of system scenarios. Initial system set-up for the proof-of-concept consists of short distance wireless point-to-point connection between two full-duplex transceivers. Initial and indicative performance targets for the full-duplex transceiver have been defined in this document. Final selection of the combination of antenna, RF and digital baseband solutions for the proof-of-concept will be made after the performance of individual cancellation solutions is studied and clarified further in the DUPLO project.

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