



DUPLO Deliverable D6.4

Dissemination report

Project Number:	316369
Project Title	Full-Duplex Radios for Local Access – DUPLO
Deliverable Type:	PU

Contractual Date of Delivery:	May 31 st , 2015
Actual Date of Delivery:	May 31 st , 2015
Editor(s):	Dirk-Jan van den Broek
Author(s):	Dirk-Jan van den Broek, Bram Nauta, Kari Rikkinen, Eric Klumperink
Workpackage:	WP6
Estimated person months:	2
Security:	PU
Nature:	Report
Version:	1.0

Abstract: This document details the dissemination and standardization activities of the DUPLO project. It provides an overview of published and submitted work, intellectual property, the DUPLO website and the second DUPLO workshop on full-duplex wireless.

Keyword list: Dissemination, conference, journal, website, workshop

Executive Summary

This document details the dissemination and standardization activities of the DUPLO project.

Within the 2.5-year project duration, DUPLO caught up in the emerging, but rapidly evolving state-of-the-art in full-duplex wireless and has contributed significant steps to full-duplex research. The project has achieved good visibility by presenting work at major events: the consortium has presented 23 conference papers and 13 posters and presentations. In addition, 6 journal and magazine contributions were published in major journals. Furthermore, the project has yielded one Master's thesis.

A number of papers were presented in the 2 workshops organized by the project. The first workshop was organized in the context of the 2014 International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM) conference in Oulu, Finland. The second was organized preceding the IEEE Vehicular Technology Conference (VTC) 2015-Spring, in Glasgow, Scotland. Both workshops were attended by around 40 people from academia and industry.

DUPLO has maintained a public website containing news, information on the project and organization, an overview of publications and demo videos. Also, an internal website was used as a collaboration tool.

Three submitted works are pending at the time of writing, as well as material for a book chapter.

The DUPLO project has resulted in demonstrators of two full-duplex link solutions. DUPLO has showcased these demonstrators in the second DUPLO Workshop in conjunction with the IEEE Vehicular Technology Conference (VTC) 2015-Spring, and will have another showcase at the European Conference on Networks and Communications (EUCNC).

The targeted DUPLO involvement in intellectual property rights and standardization has been limited, mostly due to the loss of the major industrial partner Renesas Mobile Europe in the early stages of the project.

Overall, the project has performed well in terms of dissemination and through good visibility, it has reduced scepticism on full-duplex wireless communication and paved the way for future research, implementation and standardization efforts.

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Abbreviations

DUPLO	full-DUPlex radios for LOcal access
FD	Full-Duplex
HD	Half-Duplex
IPR	Intellectual Property Right
IEEE	Institute of Electrical and Electronics Engineers
MIMO	Multiple-Input Multiple-Output
OFDM	Orthogonal Frequency-Division Multiplexing

1. INTRODUCTION

The DUPLO project has researched in-band full-duplex wireless communication, i.e. transmission and reception taking place concurrently in the same frequency band. Full-duplex could become an important enabler in achieving the 1000-fold increase in data traffic that is ultimately projected for the future wireless landscape of 5G.

This document provides an overview of all publications, presentations, standardization contributions and intellectual property rights (IPR's) that emerged from the project. Within the 2.5-year project duration, DUPLO caught up in the emerging, but rapidly evolving state-of-the art in full-duplex wireless and has contributed significant steps to full-duplex research. The project has achieved good visibility by presenting work at major events and publishing in major journals.

Chapter 2 provides a detailed list of the project output:

- 13 posters and presentations
- 23 conference papers
- 6 journal and magazine contributions
- 1 master's thesis
- participation in 1 standardization activity
- 3 submitted works at the time of writing.

Chapter 2 also describes the public website and the internal website used for collaboration.

Chapter 3 reports on the second DUPLO workshop on full-duplex radios, organized in the context of the IEEE Vehicular Technology Conference (VTC) 2015-Spring, in Glasgow, Scotland.

Chapter 4 concludes this final report on dissemination.

2. DETAILED LIST OF PUBLICATIONS

This chapter provides a detailed list of published and submitted work, organized by:

1. posters and presentations
2. conference papers
3. journal and magazine contributions
4. book contributions and theses
5. IPRs and standardization activities
6. submitted works at the time of writing
7. public website
8. internal website

2.1. List of posters and presentations

Title: DUPLO, Scenarios, system requirements and standardization objectives

Publication date: February 27, 2013

Authors: Kari Rikkinen

Event: EU FP7 RAS Cluster meeting, Brussels, Belgium

Description: This presentation outlines the DUPLO consortium structure, its objectives and the resulting requirements on system-level.

Title: DUPLO Project Summary Sheet

Publication date: February, 2013

Authors: Kari Rikkinen

Event: FP7 ICT Call 8 Project Portfolio

Description: This leaflet summarizes the DUPLO objectives, technical approach, expected issues and the expected impact on the European mobile communications industry.

Title: Exploring Practical, Full-Duplex Wireless

Publication date: April 19, 2013

Authors: Dirk-Jan van den Broek, Eric Klumperink, Bram Nauta

Event: Union Radio-Scientifique Internationale (URSI) Benelux Forum 2013, Eindhoven, the Netherlands

Description: This poster illustrates the concept of full-duplex wireless, the issue of self-interference and the implications on transceiver level.

Title: Full-duplex Systems and Radios

Publication date: May 14, 2013

Authors: Visa Tapio

Event: University of Oulu DCE Research Highlights Seminar, Oulu, Finland

Description: This presentation outlined the DUPLO consortium structure and its technical objectives.

Title: DUPLO: Full-Duplex Radios for Local Access

Publication date: July 3-5, 2013

Authors: Kari Rikkinen

Event: Future Network and Mobile Summit (FUNEMS) 2013, Lisbon, Portugal

Description: This poster presentation introduces the DUPLO project structure and discusses the system scenarios which have been selected as its research framework.

Title: A new full-duplex radio transmission paradigm

Event date: March 17, 2014

Authors: Kari Rikkinen

Event: Pre-FIA workshop (Future Internet Assembly) 2014, Athens, Greece

Description: This presentation introduces the DUPLO project, the Full-Duplex transmission paradigm, prior art, system-level considerations and initial self-interference channel measurements.

Title: Digital Self-Interference Cancellation in Full-Duplex Tranceivers

Event date: June 4, 2014

Authors: Visa Tapio, Mir Ghoraishi

Event: DUPLO Workshop on Full-Duplex @ International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM) 2014, Oulu, Finland

Description: This workshop presentation dealt with the digital baseband aspects of Full Duplex interference cancelling. Starting from the overall system architecture, the focus was put on DSP techniques like filters and phase shifters.

Title: DUPLO main achievements and exploitation prospects

Event date: October, 2014

Authors: Kari Rikkinen

Event: Net-Tech Future Coordination Meeting

Description: This short document introduces the DUPLO project, its main achievements and future exploitation prospects and priorities.

Title: A Self-Interference Cancelling Receiver for In-Band Full-Duplex Wireless

Event date: March 24 - 25, 2015

Authors: Dirk- Jan van den Broek, Eric Klumperink, Bram Nauta

Event: ICT.Open 2015, Amersfoort, Netherlands

Description: This poster presents an SI cancelling receiver implemented in 65nm CMOS, based on a highly linear vector modulator downmixer for up to 27dB SI-cancellation and 69dB SI-to-noise-and-distortion ratio in 16.25MHz bandwidth.

Title: DUPLO – Full-Duplex Radios for Local Access, Project main achievements and exploitation plan

Event date: March 25, 2015

Authors: Kari Rikkinen

Event: NetFutures 2015 RAS workshop, Brussels, Belgium

Description: This presentation summarizes the DUPLO project main results and exploitation prospects.

Title: Interference Rejection exploiting Switched- R-C Techniques Compatible with CMOS

Event date: May, 2015

Authors: Eric Klumperink, Dirk- Jan van den Broek, Bram Nauta

Event: IEEE Radio Frequency Integrated Circuits Symposium (RFIC) and International Microwave Symposium (IMS) 2015, Phoenix, USA

Description: This workshop presentation describes two ways of dealing with strong interferers at circuit level using linear, passive components. The first relies on N-path filters to create sharp, tuneable notch filters to reject nearby blockers. The second is a full-duplex self-interference cancelling technique for in-band interference, relying on a switched-resistor mixer-first architecture.

Title: Electrical-Balance Duplexing for RF Self-Interference Cancellation to Enable In-Band Full-Duplex

Event date: May, 2015

Authors: Barend van Liempd

Event: IEEE Radio Frequency Integrated Circuits Symposium (RFIC) and International Microwave Symposium (IMS) 2015, Phoenix, USA

Description: This workshop presentation discusses how electrical-balance duplexers can be used in full-duplex and frequency-division duplexing systems. It discusses state-of-the-art linear duplexers developed partially within the DUPLO project.

Title: Exhibition proposal – Full-Duplex Radios for Local Access

Event date: June 30 – July 2, 2015 (Accepted for presentation)

Authors: Kari Rikkinen

Event: European Conference on Networks and Communications (EUCNC) 2015, Paris, France

Description: The proof-of-concept DUPLO demonstrator will be showcased at this exhibition. This hardware setup will demonstrate the feasibility of the developed transceiver prototypes for full-duplex wireless communication and its suitability for future 5G networks. The communication performance between two radio transceiver nodes will be quantified based on live measurements over different measurement conditions and scenarios.

2.2. List of conference and workshop papers

Title: Full-Duplex Link Performance under Consideration of Error Vector Magnitude

Event date: April 6-9, 2014

Authors: Wei Li, Jorma Lilleberg

Event: IEEE Wireless Communications and Networking Conference (WCNC) 2014, Istanbul, Turkey

Description: This conference paper examines the effect of transmitter Error Vector Magnitude (EVM) on the performance of a full-duplex bi-directional link. It is assumed the EVM content of the self-interference can be suppressed only by antenna isolation and RF cancellation, whereas digital cancellation only suppresses the deterministic signal content of the self-interference. The analysis is performed by comparing the rate regions and the transmission power efficiencies of the corresponding half-duplex and full-duplex links.

Title: Self-interference Channel for Full-Duplex Transceivers

Event date: April 6-9, 2014

Authors: Alok Sethi, Visa Tapio, Markku Juntti

Event: IEEE Wireless Communications and Networking Conference (WCNC) 2014, Istanbul, Turkey

Description: In this paper the self-interference channel for full duplex transceivers is investigated. The SI channel was measured with a narrow-band measurement technique and UWB antennas mounted on a laptop frame, in a variety of antenna orientations and environments. The channel showed a coherence bandwidth between 1 and 4 MHz and a considerable amount of direct coupling of the signal through the mounting chassis.

Title: On the Average Spectral Efficiency of Interference-Limited Full-Duplex Networks

Event date: June 4, 2014

Authors: Hirley Alves, Carlos Lima, Pedro Nardelli, Richard Demo Souza, Matti Latva-aho

Event: DUPLO Workshop on Full-Duplex @ International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM) 2014, Oulu, Finland

Description: This workshop-oriented paper studies how dense deployments of small cells with full duplex technology perform under various network configurations and channel conditions. Self-interference, co-channel interference and inter-user interference are considered, and statistical models are used to describe the network deployment and channel conditions.

Title: RF Self-Interference Cancellation for Full-Duplex

Event date: June 4, 2014

Authors: Barend van Liempd, Björn Debaillie, Jan Craninckx, Cristina Lavín, Carmen Palacios, S. Malotiaux, J.R. Long, Dirk-Jan van den Broek, Eric Klumperink

Event: DUPLO Workshop on Full-Duplex @ International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM) 2014, Oulu, Finland

Description: This workshop-oriented paper presents an electrical balance duplexer and a dual-polarized antenna technique for RF self-interference cancellation in small-form-factor full-duplex devices. SI-cancellation and other performance measurements are included.

Title: Full-Duplex Communications in Interference Networks Under Composite Fading Channel

Event date: June 23-26, 2014

Authors: Carlos Lima, Pedro Nardelli, Matti Latva-aho

Event: IEEE European Conference on Networks and Communications (EUCNC) 2014, Bologna, Italy
Description: This paper investigates how dense deployments of small cells perform when full-duplex nodes communicate under composite fading channels. A mathematical framework is developed to approximate the aggregate interference at the user of interest under various network configurations and fading conditions. The performance of full-duplex networks compares favourably against half-duplex networks for SI-cancellation capabilities exceeding 90 dB.

Title: A Full-Duplex Transceiver Prototype with In-System Automated Tuning of the RF Self-Interference Cancellation

Event date: November 26-27, 2014

Authors: Mina Mikhael, Barend van Liempd, Jan Craninckx, Rafik Guindi, Björn Debaillie

Event: International Conference on 5G for Ubiquitous Connectivity (5GU), Levi, Finland

Description: This paper describes an automated tuning algorithm for a full-duplex transceiver featuring a tunable electrical balance duplexer. The algorithm relies on standard training sequences for its operation and does not require additional RF or analog hardware.

Title: A $>+70$ dBm IIP3 Single-Ended Electrical-Balance Duplexer in 0.18 μ m SOI CMOS

Event date: February 20-27, 2015

Authors: Barend van Liempd, Benjamin Hershberg, Kuba Raczkowski, Saneaki Ariumi, Udo Karthaus, Karl-Frederik Bink, Jan Craninckx

Event: IEEE International Solid State Circuits Conference (ISSCC) 2015, San Francisco, USA

Description: This paper describes an electrical-balance duplexer achieving state-of-the-art linearity and insertion loss performance, enabled by RF SOI CMOS technology.

Title: A Self-Interference Cancelling Receiver for In-Band Full-Duplex Wireless with Low Distortion under Cancellation of Strong TX leakage

Event date: February 20-27, 2015

Authors: Dirk-Jan van den Broek, Eric Klumperink, Bram Nauta

Event: IEEE International Solid State Circuits Conference (ISSCC) 2015, San Francisco, USA

Description: This paper presents a self-interference cancelling receiver based on a switched-resistor vector modulator downmixer that offers up to 27dB of cancellation while maintaining sufficient linearity for up to 42dB digital cancellation. Combined with a moderate 20dB antenna isolation, it can achieve up to 89dB link budget in 16.25MHz BW.

Title: Joint Subcarrier and Power Allocation for Sum-Rate Maximization in OFDMA Full-Duplex Systems

Event date: May 11-15, 2015

Authors: Ali Cirik, Kari Rikkinen, Matti Latva-aho

Event: IEEE Vehicular Technology Conference (VTC) Spring 2015 (Main conference), Glasgow, Schotland

Description: This paper focusses on the joint subcarrier and power allocation for an orthogonal frequency division multiple access (OFDMA) full-duplex system with the goal of maximizing the sum-

rate subject to power constraints at the base station and uplink users, and subcarrier constraints. A hybrid scheduler that switches between HD and FD is proposed to maximize the sum-rate.

Title: RF Self-Interference Reduction Techniques for Compact Full-Duplex Radios

Event date: May 11-15, 2015

Authors: Björn Debaillie, Dirk-Jan van den Broek, Cristina Lavín, Barend van Liempd, Eric Klumperink, Carmen Palacios, Jan Craninckx, Bram Nauta

Event: IEEE Vehicular Technology Conference (VTC) Spring 2015 (DUPLO Workshop), Glasgow, Schotland

Description: This paper describes the three prototyped RF self-interference reduction techniques for full-duplex wireless links that were developed within the DUPLO project. These solutions specifically target integration in compact radios. Concretely, a self-interference cancelling front-end, a dual-polarized antenna, and an electrical balance duplexer are presented. Each technique offers specific benefits in terms of implementation density, self-interference rejection, bandwidth and flexibility.

Title: Hybrid Half- and Full-Duplex Communications Under Correlated Lognormal Shadowing

Event date: May 11-15, 2015

Authors: Carlos H. M. de Lima, Hirley Alves, Pedro H. J. Nardelli, Matti Latva-aho

Event: IEEE Vehicular Technology Conference (VTC) Spring 2015 (DUPLO Workshop), Glasgow, Schotland

Description: This paper presents an investigation of full-duplex base stations serving half-duplex user equipment on the uplink and downlink simultaneously. Users are modeled as a homogeneous Poisson point process while the channel is modeled as a composite fading with correlated Lognormal shadowing and Nakagami-m fading. The signal-to-interference-ratio is characterized at a user of interest, and the network outage probability is evaluated. The model accounts for the cross-correlation between the user of interest and a random co-site interferer within range.

Title: Full-Duplex Relaying Systems Subject to Co-channel Interference and Noise in Nakagami-m Fading

Event date: May 11-15, 2015

Authors: Hirley Alves, Richard D. Souza, Daniel B. da Costa, Matti Latva-aho

Event: IEEE Vehicular Technology Conference (VTC) Spring 2015 (DUPLO Workshop), Glasgow, Schotland

Description: This paper investigates the performance of dual-hop full-duplex relaying schemes subject to co-channel interference (CCI) and noise. Two main scenarios are considered: in the first scenario, the link between the source and destination is seen as interference and, in the second one, it is seen as useful information. In both schemes, the effect of self-interference at the relay is taken into account. Based on closed-form expressions, it is shown that CCI at the relay is more harmful for the system performance than CCI at the destination.

Title: Game Theory Based Radio Resource Allocation for Full-Duplex Systems

Event date: May 11-15, 2015

Authors, affiliations: Mohammed Al-Imari, Mir Ghorashi, Pei Xiao, Rahim Tafazolli

Event: IEEE Vehicular Technology Conference (VTC) Spring 2015 (DUPLO Workshop), Glasgow, Schotland

Description: This paper focuses on resource allocation in systems with full-duplex base stations and half-duplex user-equipment. In such systems, the resource allocation has to account for self-interference and inter-user interference. An iterative resource allocation algorithm is proposed based on game theory by modelling the problem as a noncooperative game between the uplink and downlink channels.

Title: Fairness Considerations in Full-Duplex MIMO Interference Channels

Event date: April 19 – 24, 2015

Authors: Ali Cagatay Cirik, Yue Rong, Yingbo Hua, Matti Latva-aho

Event: IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2015, Brisbane, Australia

Description: This paper addresses the proportional fairness issue in a system with multiple full-duplex MIMO links. This is particularly relevant for asymmetric links.

Title: A Self-Interference Cancelling Front-End for In-Band Full-Duplex Wireless and its Phase Noise Performance

Event date: May 17-19, 2015

Authors, affiliations: Dirk-Jan van den Broek, Eric A.M. Klumperink, Bram Nauta

Event: IEEE Radio Frequency Integrated Circuits Symposium (RFIC) and International Microwave Symposium (IMS) 2015, Phoenix, USA

Description: This paper describes the transmitter performance and phase noise rejection achieved by the SI-cancelling full-duplex front-end developed within DUPLO.

Title: An Electrical-Balance Duplexer for In-Band Full-Duplex with $<-85\text{dBm}$ In-Band Distortion at $+10\text{dBm}$ TX-power

Event date: September 14-18, 2015 (Accepted for publication)

Authors, affiliations: Barend van Liempd, Benjamin Hershberg, Björn Debaillie, Piet Wambacq, Jan Craninckx

Event: IEEE European Solid State Circuits Conference (ESSCIRC) 2015, Graz, Austria

Description: This paper describes the distortion performance of an electrical balance duplexer prototype for full-duplex and frequency-division duplexing, and its implications for the achievable full-duplex link budget.

Title: In-band Full-Duplex Transceiver Technology for 5G Mobile Networks

Event date: September 14-18, 2015 (Accepted for publication)

Authors: B. Debaillie, B. van Liempd, B. Hershberg, J. Craninckx, K. Rikkinen, D.J. van den Broek, E.A.M.Klumperink, B.Nauta

Event: IEEE European Solid State Circuits Conference (ESSCIRC) 2015, Graz, Austria

Description: This invited paper describes the DUPLO circuit work for full-duplex in a 5G context, i.e. the EB-duplexer and the self-interference cancelling front-end.

Title: Cross-Layer Approach for Asymmetric Traffic Accommodation in Full-Duplex Wireless Network

Event date: June 29-July 2, 2015 (Accepted for publication)

Authors: Hassan Malik, Mir Ghorashi, Rahim Tafazolli

Event: European Conference on Networks and Communications (EUCNC) 2015, Paris, France

Description: This paper describes a cross-layer resource-allocation model to accommodate asymmetric traffic in (inherently more symmetric) full-duplex links.

Title: Resource Allocation in Full-Duplex OFDMA Systems with Partial Channel State Information

Event date: July 12-15, 2015 (Accepted for publication)

Authors: Ali Cagatay Cirik, Kari Rikkinen, Rui Wang, Yingbo Hua

Event: IEEE China Summit & International Conference on Signal and Information Processing (ChinaSIP) 2015, Chengdu, China

Description: This paper focuses on joint subcarrier and rate allocation for an orthogonal frequency division multiple access full-duplex system. The goal is to maximize the system's successful transmission rate subject to power constraints at the base station and uplink users, and subcarrier constraints.

Title: Digital Cancellation Design for Full-Duplex Point-to-Point MIMO Systems

Event date: August 24-28, 2015 (Accepted for publication)

Authors: Dandan Liang, Pei Xiao, Gaojie Chen, Mir Ghorashi, Rahim Tafazolli

Event: IEEE International Wireless Communications & Mobile Computing Conference (IWCMC) 2015, Dubrovnik, Croatia

Description: This paper proposes a hybrid method of mitigating the effects of the residual self-interference that is imposed by the signal propagation and analog/digital circuit non-idealities for Full-Duplex (FD) point-to-point multiple-input multiple-output (MIMO).

Title: Subband Approach for Wideband Self-Interference Cancellation in Full-Duplex Transceiver

Event date: August 24-28, 2015 (Accepted for publication)

Authors: Mir Ghorashi, Wei Jiang, Pei Xiao, Rahim Tafazolli

Event: IEEE International Wireless Communications & Mobile Computing Conference (IWCMC) 2015, Dubrovnik, Croatia

Description: This paper proposes a subband approach to deal with frequency-selective self-interference.

Title: Cross-Layer Approach for Asymmetric Traffic Accommodation in Full-Duplex Wireless Network

Event date: June 29-July 2, 2015 (Accepted for publication)

Authors: Hassan Malik, Mir Ghorashi, Rahim Tafazolli

Event: European Conference on Networks and Communications (EUCNC) 2015, Paris, France

Description: This paper describes a cross-layer resource-allocation model to accommodate asymmetric traffic in (inherently more symmetric) full-duplex links.

Title: A full duplex MAC protocol for wireless networks

Event date: August 24-28, 2015 (Accepted for publication)

Authors: Jawad Seddar, Hicham Khalife, Wassim Al Safwi, Vania Conan

Event; IEEE International Wireless Communications & Mobile Computing Conference (IWCMC) 2015, Dubrovnik, Croatia

Description: This paper proposes propose a new MAC protocol targeting bidirectional full duplex wireless networks. It reserves resources and adapts frame sizes based on the handshake between communicating nodes. Most importantly, this protocol requires minor changes for backward compatibility with IEEE 802.11 protocol.

2.3. List of journal and magazine papers

Title: On Rate Region Analysis of Half- and Full-Duplex OFDM Communication Links

Publication date: June 12, 2014

Authors: Wei Li, Jorma Lilleberg, Kari Rikkinen

Published in: IEEE Journal on Selected Areas in Communications (JSAC), Volume: 32, Issue: 9, pp. 1688 – 1698

Description: This paper analyzes the rate regions of half- and full-duplex OFDM links, taking into account the non-ideality of practical transceivers. Three stages of self-interference suppression are taken into account, with different capabilities of suppressing the self-interference and its associated EVM. Two optimal power allocation strategies are proposed for such links and the achieved rate regions are compared under frequency-flat and frequency-selective environments.

Title: Analog / RF solutions Enabling Compact Full-Duplex Radios

Publication date: June 12, 2014

Authors: Björn Debaillie, Dirk-Jan van den Broek, Cristina Lavin, Barend van Liempd, Eric A.M. Klumperink, Carmen Palacios, Jan Craninckx, Bram Nauta, Aarno Parssinen

Published in: IEEE Journal on Selected Areas in Communications (JSAC), Volume: 32, Issue: 9, pp. 1662 – 1673

Description: This paper describes the challenges in achieving full-duplex wireless in a compact form-factor. Feasibility bottlenecks for integrated full-duplex transceivers are identified analytically and their impact on full-duplex link-budgets is expressed in equations. Two designs are proposed that provide attractive isolation in the analog RF domain in a compact form-factor: 1) A dual-polarized antenna + tunable cancellation circuit, 2) An electrical balance isolator / duplexer + single-port antenna.

Title: On the Spectral Efficiency of Full-Duplex Small Cell Wireless Systems

Publication date: July 1, 2014

Authors: Dan Nguyen, Le-Nam Tran, Pekka Pirinen, Matti Latva-aho

Published in: IEEE Transactions on Wireless Communications, Volume: 13, Issue: 9, pp. 4896 - 4910

Description: This paper investigates the spectral efficiency of full-duplex small cell wireless systems consisting of a full-duplex capable base station and multiple half-duplex users. Two convergent beamformer design algorithms are proposed for such systems. Extensive numerical experiments illustrate the gains of the full-duplex system.

Title: Weighted Sum-Rate Maximization for Full-Duplex MIMO Interference Channels

Publication date: October, 2015 (Accepted for publication)

Authors: Ali Cagatay Cirik, Rui Wang, Yingbo Hua, Matti Latva-aho

Published in: IEEE Transactions on Communications

Description: This paper describes the optimization problem of multiple full-duplex mimo links suffering from self-interference and inter-user interference.

Title: An Integrated Self-Interference Cancelling Receiver for In-Band Full-Duplex Wireless Communication

Submission date: April, 2015 (Invited paper, conditionally accepted)

Authors: Dirk-Jan van den Broek, Eric Klumperink, Bram Nauta

Submitted to: IEEE Journal of Solid-State Circuits (JSSC), special issue on ISSCC 2015

Description: This paper expands on the ISSCC conference paper describing the highly linear SI-cancelling receiver with vector modulator downmixer. It provides more design considerations and a noise analysis of the receiver.

Title: Fairness Considerations for Full Duplex Multi-user MIMO Systems

Publication date: 2015 (Accepted for publication)

Authors: Ali Cagatay Cirik

Submitted to: IEEE Wireless Communication Letters (WCL)

Description: This paper describes a cellular system with a full-duplex base station serving multiple uplink and downlink users simultaneously, where all the nodes are equipped with multiple antennas. The self-interference at the co-channel interference caused by the UL users on the DL users are both taken into account. A beamforming algorithm is proposed that provides a good balance between throughput and fairness among users.

2.4. List of book contributions and theses

Title: Self-Interference Channel and Analog Baseband Cancellation for Full-Duplex Transceiver

Publication date: August 26, 2013

Authors: Alok Sethi

Published in: Master's Thesis, University of Oulu, Finland

Description: This thesis describes the properties of the self-interference channel and defines an analog baseband cancellation mechanism for full duplex (FD) transceiver. An OFDM-based transceiver for full-duplex was simulated using MATLAB.

2.5. List of IPR's and standardization contributions

Title: Full-duplex Technology for HEW (High-Efficiency WLAN)

Publication date: July 15, 2013

Authors: André Bourdoux, Barend van Liempd, Björn Debaillie

Event: IEEE 802.11 #140 Plenary Meeting, Geneva, Switzerland

Description: The goal of this presentation is to start a reflexion process in the high-efficiency WLAN standardization group about the relevance/timeliness of full-duplex technology for high-efficiency WLAN.

Title: Bi-Direction Channel Tracking

Filing date: July 12, 2013

Assignee: Renesas Mobile Corporation

Patent application number: UK Patent No. 1312553.9

Description: This patent relates to methods, apparatuses and a computer program product for sub-carrier based bi-directional channel tracking.

2.6. List of submitted work

Title: Throughput Improvement by User Selection in Hybrid Full/Half Duplex Device-to-Device Cellular System

Submission date: April, 2015

Authors: Gaojie Chen, Mir Ghorraishi, Pei Xiao, Rahim Tafazolli

Submitted to: IEEE International Symposium on Wireless Communication Systems (ISWCS) 2015, Brussels, Belgium

Description: This paper studies the best cellular user selection in hybrid half / full-duplex device-to-device cellular networks. Closed-form expressions are derived for the signal-to-noise-plus-interference ratio and outage probability.

Title: QoS Considerations for Full Duplex Multi-user MIMO Systems

Submission date: February, 2015

Authors: Ali Cagatay Cirik , Omid Taghizadehy, Rudolf Mathary, Matti Latva-aho

Submitted to: IEEE Global communications conference, exhibition and industry forum (GLOBECOM) 2015, San Diego, USA

Description: This paper considers a full-duplex multi-user MIMO system where the base station serves multiple uplink and downlink users simultaneously. We focus on the Quality-of-Service (QoS) problem, in which the transmitted sum-power at the BS and UL users is minimized subject to minimum rate constraints at each user of the system.

Title: Full-duplex transmission in small area radio communication systems

Submission date: May, 2015

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Submitted to: IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (CAMAD)

Description: This paper introduces potential use cases for full-duplex transmission in small area radio communication systems, and evaluates the achievable performance gains of full- duplex transmission over half-duplex transmission in different network set-ups. Additionally, this paper introduces DUPLO full- duplex transceiver hardware demonstrator and characterizes with practical measurements the achievable performance in short-range communications.

2.7. DUPLO public website

DUPLO has maintained a public website to showcase the project organization, news, recent results and publications. It contains the following items:

- General info
- Project structure
- Objectives
- Partners
- Deliverables
- Dissemination
- Links
- Contact

Website address: <http://www.fp7-duplo.eu/>

A screenshot of the website is shown below. At the time of writing, over 16000 site visits were counted.



Figure 1: The appearance of the DUPLO public website.

2.8. DUPLO internal website / collaboration tool

For internal collaboration, the consortium used Confluence by Atlassian. Each work package had its own sections for efficient collaboration on draft documents, sharing measurement data, preparing meeting agendas etc. This collaboration tool was extensively used.

3. SUMMARY OF 2ND DUPLO WORKSHOP AT VTC SPRING 2015

On Monday May 11th 2015, a second workshop was organized on full-duplex radios and systems as part of the IEEE 81st Vehicular Technology (VTC 2015-Spring) in Glasgow, Scotland. The workshop was organized in co-operation with the EU FP7 DUPLO project.

The event lasted from 8.30 a.m. to 5 p.m. and took place at the University of Strathclyde, Glasgow. Programme chairs were Kari Rikkinen from the University of Oulu and Bram Nauta from the University of Twente.

The programme consisted of four sessions:

- Full-Duplex Transmission in Wireless Networks
- Full-duplex Transceivers
- Full-Duplex Transceiver and System Solutions
- Panel Discussion *'The feasibility of full-duplex technology as the solution for future 5G systems'*

In addition, there was a **DUPLO demonstration** of a full-duplex point-to-point link based on the dual-polarized antenna and active cancellation circuitry developed within WP2 and integrated with digital cancellation algorithms in WP5.

Around 40 people attended the workshop.

<http://www.fp7-duplo.eu/index.php/dissemination/78-noticias/115-second-workshop>

3.1. Introduction

The foreseen huge growth in mobile and wireless traffic volume and number of wirelessly connected devices by 2020 call for new innovative solutions that can exploit the finite radio resources more efficiently. Full-duplex wireless transmission, where a node can send and receive at the same time in the same frequency band, opens new possibilities for improving wireless communication system performance. The full-duplex transmission paradigm has several potential use cases in wireless networks, including e.g. backhaul connections, relays, and connections between base stations and devices. However, the paradigm sets challenges to wireless transceiver implementation due to very large self-interference cancellation requirement in the full-duplex transceiver. Successful solving of the implementation challenges paves path for introducing full-duplex transmission paradigm to future 5G systems.

This workshop will look at the latest advances in research and development of novel full-duplex transceiver solutions and system applications and discuss applicability of the technology for future evolution of wireless communications systems.

3.2. Program

Workshop opening (08:30)

Kari Rikkinen (University of Oulu)

Kari welcomes the speakers and gives a brief introduction of the topics and the organization of the day. He explains the composition of the DUPLO consortium and motivation of the workshop, hoping the discussions will lead to wider acceptance of full-duplex and possible inclusion in future 5G standards.

Full-Duplex Transmission in Wireless Networks (8:40-10:10)

Full-duplex self-backhauling for small-cell 5G networks (Invited)

Risto Wichman / Aalto University, Finland

Professor Risto Wichman opens the workshop by pointing out that the bulk of traffic in 5G is asymmetric (towards the user), yielding not a good use case for full-duplex. Relaying applications however, such as self-backhauling, are more symmetric and therefore promising application scenarios for FD, helping to achieve the ultra-reliable links projected for 5G.



Professor Risto Wichman presenting the work of Aalto University.

Hybrid Half- and Full-Duplex Communications Under Correlated Lognormal Shadowing

Carlos Lima / Sao Paulo State University (UNESP), Brasil

Hirley Alves, Pedro Nardelli, Matti Latva-aho / University of Oulu, Finland

Hirley Alves presents an investigation of full-duplex base stations serving half-duplex user equipment on the uplink and downlink simultaneously. Users are modeled as a homogeneous Poisson point process while the channel is modeled as a composite fading with correlated Lognormal shadowing and Nakagami-m fading. The signal-to-interference-ratio is characterized at an user of interest, and

the network outage probability is evaluated. The model accounts for the cross-correlation between the user of interest and a random co-site interferer within range. This provides valuable insight on how the hybrid network performs under the assumption of correlated shadowing. When this correlation is low, the user of interest can achieve higher data rate at expense of high outage; however, if the distance to the serving base station is short and the cross correlation is high, a satisfactory data rate can be sustained at low outage.



Hirley Alves presenting their model for full-duplex base-stations and half-duplex user equipment.

Game Theory Based Radio Resource Allocation for Full-Duplex Systems (DUPLO)

Mohammed Al-Imari, Mir Ghorashi, Pei Xiao, Rahim Tafazolli/University of Surrey, UK

Mir Ghorashi presents this DUPLO paper on resource allocation in hybrid systems. In systems with full-duplex base stations and half-duplex user-equipment, the resource allocation has to account for self-interference and inter-user interference. This makes the problem coupled between uplink and downlink channels, and it can be formulated as joint uplink and downlink sum-rate maximization. As the problem is non-convex, an iterative algorithm is proposed based on game theory by modelling the problem as a noncooperative game between the uplink and downlink channels. The algorithm iteratively carries out optimal uplink and downlink resource allocation until a Nash equilibrium is achieved. Simulation results show that the algorithm achieves fast convergence, and can significantly improve the full-duplex performance comparing to the equal resource allocation approach. Furthermore, the full-duplex systems with the proposed algorithm can achieve considerable gains in spectral efficiency, that reach up to 40%, compared to half-duplex systems.



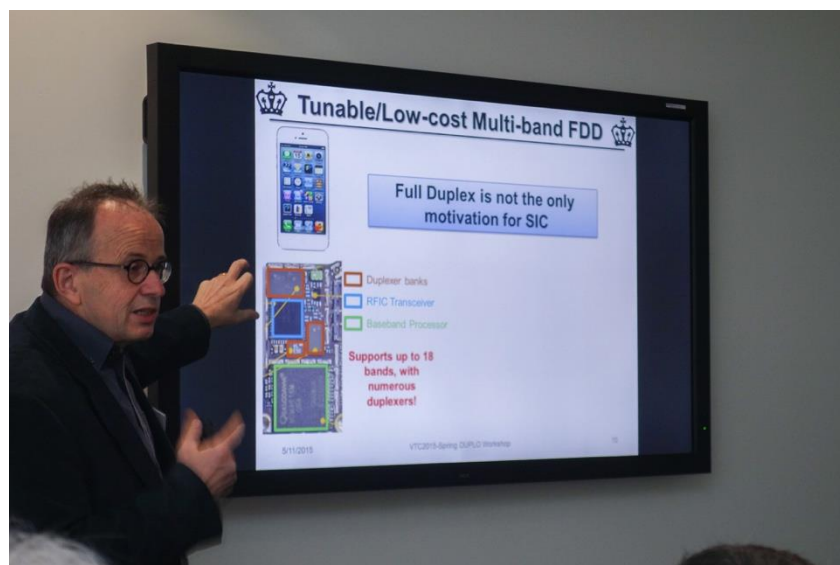
Mir Ghoraihi presenting the work of the University of Surrey on hybrid FD-HD resource allocation.

Full-duplex Transceiver (10:30-12:00)

Recent Developments in Fully-Integrated RF Self-Interference Cancellation for Frequency-Division- and Full-Duplex Radios

Jin Zhou, Harish Krishnaswamy/Columbia University, USA

Due to the unfortunate absence of Mr. Krishnaswamy, this presentation was given by Eric Klumperink from the University of Twente. In this paper, Columbia University presents recent developments in fully-integrated RF self-interference cancellation techniques. RF self-interference cancellation relaxes duplexer isolation requirements in frequency-division-duplex radios, enabling compact/tunable duplexers. RF SIC is also critical for full-duplex radios where extremely-high levels of SIC must be achieved, necessitating SIC at various points in the receiver chain. While active RF SIC is potentially compact and highly reconfigurable, the use of active circuitry in the canceller introduces noise, distortion and power dissipation challenges. Furthermore, and particularly for fully-integrated silicon-based SIC implementations, the bandwidth (BW) of RF SIC is limited by the frequency selectivity of the antenna interface and the wireless self-interference channel.



Eric Klumperink presenting the FD/FDD SI-cancellation work of Columbia University.

RF Self-Interference Reduction Techniques for Compact Full Duplex Radios (DUPLO)

Björn Debaillie, Barend van Liempd, Jan Craninckx/IMEC, Belgium

Dirk Jan van den Broek, Eric Klumperink, Bram Nauta/ University of Twente, The Netherlands

Cristina Lavin, Carmen Palacios/TTI, Spain

This paper describes the three RF self-interference reduction techniques for full-duplex wireless links that were developed within the DUPLO project. These solutions specifically target integration in compact radios. Concretely, a self-interference cancelling front-end, a dual-polarized antenna, and an electrical balance duplexer are presented. Each technique offers specific benefits in terms of implementation density, self-interference rejection, bandwidth and flexibility. Depending on their characteristics, they can be adopted in different next-generation full-duplex applications and standards. All concepts are prototyped, and achieve at least 45dB of self-interference reduction over more than 10MHz bandwidth.

A Widely Tunable Full Duplex Transceiver Combining Electrical Balance Isolation and Analog Cancellation

Leo Laughlin, Chunqing Zhang, Mark Beach, Kevin Morris/University of Bristol, UK

John Haine/u-blox, Switzerland

The University of Bristol is investigating electrical balance duplexers for full duplex. These can provide high transmit-to-receive isolation whilst facilitating transmission and reception from a single antenna, can be implemented on-chip, and are widely tunable, making this an attractive technology for implementing full duplex architectures in small form factor devices. This paper presents measurements from a novel hardware prototype full-duplex transceiver architecture combining electrical balance and active analog cancellation. The prototype duplexer achieves >80dB transmit-to-receive isolation over a 20MHz bandwidth at both 890MHz and 1890MHz, exceeding the performance of antenna separation architectures where the antenna isolation is limited to the levels achievable in hand held devices.



Leo Laughlin answering the questions arising from his presentation.

Full-Duplex Transceiver and System Solutions (13:30-15:00)

Wideband Self-Adaptive RF Cancellation Circuit for Full-Duplex Radio: Operating Principle and Measurements

Timo Huusari, Petteri Liikkanen, Dani Korpi, Mikko Valkama / Tampere University of Technology, Finland

Yang-Seok Choi, Shilpa Talwar / Intel corp, USA

Timo Huusari presents his work on a novel RF circuit architecture for self-interference cancellation in in-band full-duplex radio transceivers. The developed canceller is able to provide wideband cancellation with waveform bandwidths in the order of 100 MHz or beyond and contains also self-adaptive or self-healing features enabling automatic tracking of time-varying self-interference channel characteristics. In addition to architecture and operating principle descriptions, we also provide actual RF measurements at 2.4 GHz ISM band demonstrating the achievable cancellation levels with different bandwidths and when operating in different antenna configurations and under low-cost highly nonlinear power amplifier. In a very challenging example with a 100 MHz waveform bandwidth, around 41 dB total cancellation is obtained while the corresponding cancellation figure is close to 60 dB with the more conventional 20 MHz carrier bandwidth. Also, efficient tracking in time-varying reflection scenarios is demonstrated.



Timo Huusari of Tampere University showing their canceller prototype.

Full-Duplex Relaying Systems Subject to Co-channel Interference and Noise in Nakagami-m Fading

Hirley Alves, Matti Latva-aho/University of Oulu, Finland

Richard Demo Souza/Federal University of Technology – Parana (UTFPR), Brazil

Daniel Benevides da Costa/Federal University of Ceara (UFC), Brazil

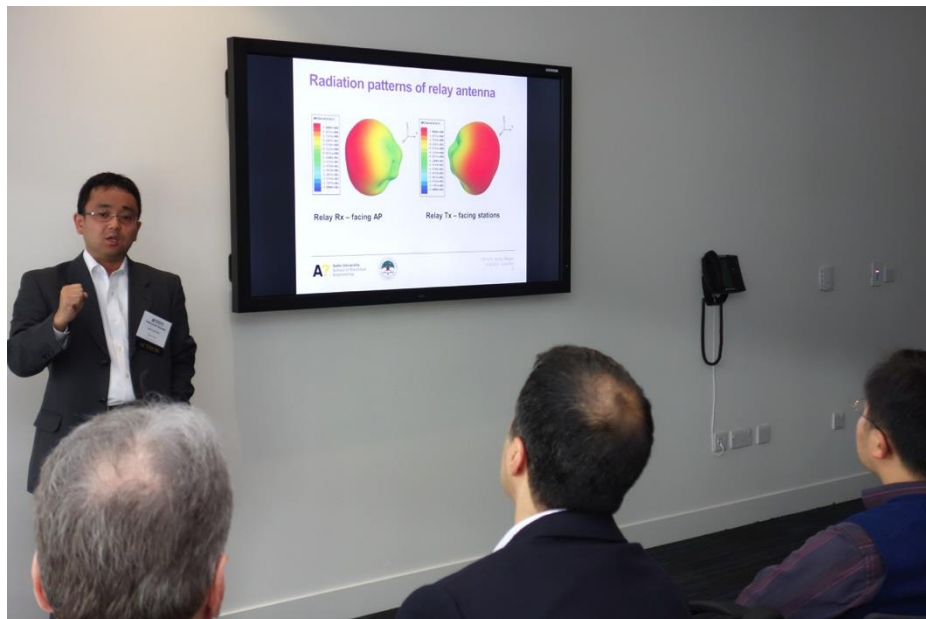
This paper investigates the performance of dual-hop full-duplex relaying schemes subject to co-channel interference (CCI) and noise. In their analysis, two main scenarios are considered: in the first scenario, the link between the source and destination is seen as interference and, in the second one, it is seen as useful information. In both schemes, the effect of self-interference at the relay is taken into account. Accurate, closed-form expressions for the outage probability are derived for the general case, in which CCI and noise are assumed at both the relay and destination. The derived expressions allow for independent non-identically distributed Nakagami-m fading. Based on these expressions, special cases (but, yet new) assuming CCI only at the relay and assuming CCI only at the destination

are examined. It is shown that CCI at the relay is more harmful for the system performance than CCI at the destination.

System-level Performance of In-Band Full-Duplex Relaying on M2M Systems at 920 MHz

*Sathya Narayana Venkatasubramanian, Katsuyuki Haneda/Aalto University, Finland
Koji Yamamoto/Kyoto University, Japan*

Aalto University presents their work on full-duplex relays. Relays can be used to improve the coverage in blind spots as well as increase the signal strength at locations where the signal from the access point undergoes fading. In-band full-duplex relaying is a promising technique which improves the spectral efficiency over traditional half-duplex relaying by relaying at the same time slot and frequency. Relays are expected to play a major role in IEEE 802.11ah systems for below 1 GHz WLAN in order to cover a large area of 1km around the access point. In this contribution, the impact of deploying in-band full-duplex relays is studied over traditional half-duplex relays in improving the coverage and throughput at the stations for M2M applications. System-level realistic evaluation of in-band full-duplex relaying is performed using the COST-2100 channel model to model the propagation and self-interference channels at 920 MHz. The channel is combined with realistic antenna design to determine the end-to-end throughput at the location of each station in a 1 sq. km area. For the downlink scenario, it is shown that such in-band full-duplex relays can increase the number of users for a given throughput over half-duplex relays. Also, a single in-band full-duplex relay can decrease the outage by 0.9% compared to half-duplex relays and 12.6% without a relay to cover 97.8% of the stations in a 1sq.km area with downlink throughput of 100kbps.



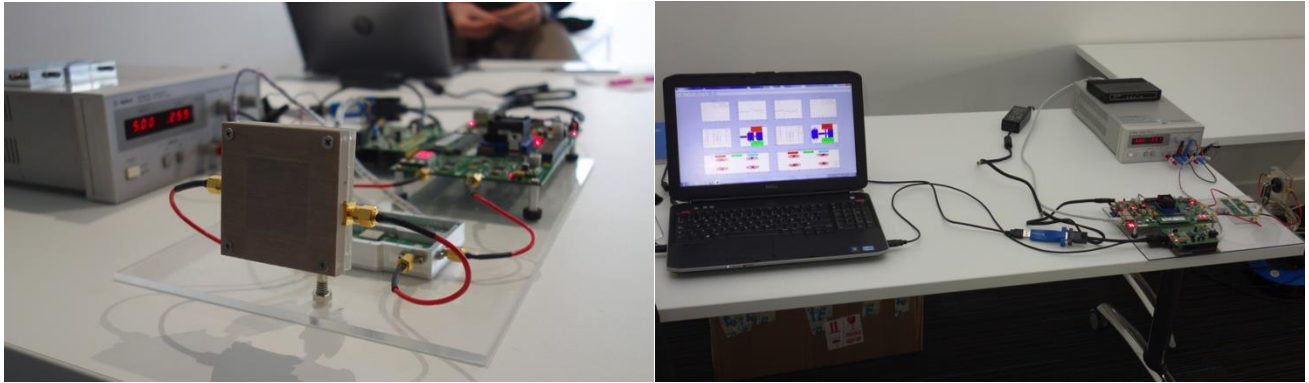
Katsuyuki Haneda presenting Aalto's work on full-duplex relaying for M2M applications, as well as a novel relay antenna design.

DUPLO full-duplex wireless demonstration

During the afternoon coffee break, DUPLO presented a full-duplex link based on two WARP radio platforms, each fitted with the cross-polarized antenna and active cancellation board developed in WP2 and integrated in WP5 with the digital cancellation algorithms running in MATLAB (WARPLAB framework).



The audience showed great interest in the DUPLO demo.



The duplo demo featuring the cross-polarized antenna and active cancellation board, showcased using a MATLAB user interface for the digital cancellation.

Panel Discussion 'The feasibility of full-duplex technology as the solution for future 5G systems' (15:30-17:00)

Moderator: Kari Rikkinen/University of Oulu

Panelists: Prof. Mark Beach / University of Bristol
 Prof. Andy Sutton / EE Network Strategy
 Dr. Ilaria Thibault / Vodafone
 Prof. Risto Wichman / Aalto University
 Dr. Senlin Zhang / ZTE

To open the panel discussion, all panel members have been asked to both provide 3 strengths for full-duplex as potential solution for 5G and 3 challenges / weaknesses to be addressed.

Prof. Mark Beach notes that from an operator standpoint, FD requires new hardware and a new network design paradigm. The potential for increased spectral efficiency is promising. He sees advantages of flexible duplexing schemes in general, not necessarily full duplex. Other possible applications are white space / cognitive radio.

With the current fragmentation of cellular bands, he foresees that flexible duplexing will prove useful before true full-duplex. Also, he foresees problems in standardization, for instance the LO radiation since most full-duplex schemes are based on mixer-first architectures. Furthermore, little is known about for instance the blocker performance of full-duplex transceivers presented so far.

He adds that Bristol is a strong proponent of the electrical balance duplexers.

Prof. Andy Sutton mentions that from 2015 to 2020, the amount of cellular traffic is expected to increase by a factor of 22, and that by 2020, 76% of this traffic will be streaming video. This is due to the screen size and resolution of mobile devices ever increasing. However, the user will perceive the same content as before, so any technique to achieve these capacities should come at low cost, including full-duplex. The market for FD is further fueled by the scarce spectrum below 10 GHz and the demand for more geographical coverage. He mentions the small cell layer will become the workhorse of cellular communication. The network needs to become a dynamic, self-healing mesh to achieve resilient, ultra-reliable communication.

Full-duplex may come into play for backhauling, and when implementing flexible mesh and relaying network structures. However, limiting factors are the form factor and the price at which the spectral efficiency comes. 5G will be implemented in multiple phases / evolutions, held back also by the evolution of mm-wave communication.

Dr. Ilaria Thibault acknowledges that with increased smartphone penetration and the demand for video streaming, the gap between traffic and revenue is increasing for mobile operators. This makes spectral efficiency especially important.

Self-interference cancellation has interesting aspects for: 1) Relays, to implement a low-latency, low-cost control plane; 2) Full-duplex uplink/downlink with half-duplex users, this allows a flexible use of resources; 3) Improved co-existence in unlicensed spectrum (e.g. using adjacent channels); 4) Better RF performance in general to allow more carrier aggregation.

Challenging aspects are the robustness to the environment, the rise of new types of interference with the FD paradigm, increased scheduling overhead and the limited scalability of FD to MIMO.

Prof. Risto Wichman points out that the 2x spectral efficiency is only reached for symmetric traffic demands, strengthening the usefulness of FD for relaying applications. Removal of the guard time required to switch between uplink and downlink can lead to lower latency relays.

Points of concern are the power efficiency, which is a major factor for 5G. Also it remains to be seen if FD is commercially viable in dense networks with many antennas. New interference mechanisms need to be studied. Also, the gains may not be significant when compared with massive MIMO.

Dr. Senlin Zhang mentions that for macrocells, transmitting at 47dBm, the SIC requirements are enormous. In cellular applications, inter-site and inter-user interference are of concern. Also, in systems with multiple antennas, SIC becomes very complex.

ZTE focuses on FD in small cell scenarios, with few antennas (up to 8). Compatibility with at least a number of antennas is important, however. They foresee the first applications of FD in relaying, self-backhauling and mm-wave backhauling. In addition, they work on beam division multiple access.

An interesting **panel discussion** follows. The panel agrees on relaying as an important early commercialization opportunity for full-duplex in cellular. Full-duplex cannot benefit from a clean slate, but has to be slowly adopted in cellular networks until a unified structure emerges. The operators are not in favor of switching between half-duplex and full-duplex modes of operation, based on their experiences with band-switching in LTE networks.

The opportunity for FD in larger form-factors should also be considered, for instance in connected cars. Besides looking forward to cellular, investigations should continue in point-to-point links, body area networks, et cetera to learn more, and to validate FD concepts. Furthermore, FD may offer interesting security aspects.



The five industry representatives during the panel session.



The panel engaged in discussion.

3.3. Technical Program Committee composition

- Visa Tapio / University of Oulu, Finland (TPC Chair)
- Jawad Seddar / Thales, France
- Ashutosh Sabharwal / Rice University, USA
- Risto Wichman / Aalto University, Finland
- Mikko Valkama / Tampere University of Technology, Finland
- Guillaume Villemaud / Insa Lyon, France
- Wilhelm Keusgen / Fraunhofer HHI, Germany
- Alex Gong / Loughborough University, UK

- *Sofie Pollin / KUL, Leuven, Belgium*
- *Amir Khandani / University of Waterloo, Canada*
- *Marcos Katz / University of Oulu, Finland*
- *Achaleshwar Sahai / Qualcomm Inc ,USA*
- *Vaneet Aggarwal / AT&T Research, USA*
- *Ahmed Eltawil / UC Irvine , USA*
- *Cristina Lavin / TTI, Spain*
- *Björn Debaillie / IMEC, Belgium*
- *Dirk Jan van den Broek / University ofTwente, Netherlands*
- *Mir Ghoraishi / University of Surrey, UK*
- *Jawad Seddar / Thales, France*

4. CONCLUSIONS

Within the 2.5-year project duration, DUPLO caught up in the emerging, but rapidly evolving state-of-the-art in full-duplex wireless and has contributed significant steps to full-duplex research. The project has achieved good visibility by presenting work at major events: the consortium has presented 23 conference papers and 13 posters and presentations. In addition, 6 journal and magazine contributions were published in major journals. Furthermore, the project has yielded one Master's thesis.

A number of papers were presented in the 2 workshops organized by the project. The first workshop was organized in the context of the 2014 International Conference on Cognitive Radio Oriented Wireless Networks (CROWNCOM) conference in Oulu, Finland. The second was organized preceding the IEEE Vehicular Technology Conference (VTC) 2015-Spring, in Glasgow, Scotland. Both workshops were attended by around 40 people from academia and industry.

DUPLO has maintained a public website containing news, information on the project and organization, an overview of publications and demo videos. Also, an internal website was used as a collaboration tool.

Three submitted works are pending at the time of writing, as well as material for a book chapter.

The DUPLO project has resulted in demonstrators of two full-duplex link solutions. DUPLO has showcased these demonstrators in the second DUPLO Workshop in conjunction with the IEEE Vehicular Technology Conference (VTC) 2015-Spring, and will have another showcase at the European Conference on Networks and Communications (EUCNC).

The targeted DUPLO involvement in intellectual property rights and standardization has been limited, mostly due to the loss of the major industrial partner Renesas Mobile Europe in the early stages of the project.

Overall, the project has performed well in terms of dissemination and through good visibility, it has reduced scepticism on full-duplex wireless communication and paved the way for future research, implementation and standardization efforts.