Abstract - This paper investigates beam forming design of joint transceiver in full-duplex wireless powered communication networks for throughput maximization, where a multi-antenna hybrid access point (H-AP) broadcasts wireless energy to two distributed dual-antenna users and the users cooperatively transmit information signals via their individually harvested energy. Furthermore, the users can recycle self-energy from their own transmitted signals. H-AP acts as a transceiver to transmit energy and receive information simultaneously and amplified and forward relaying channel is applied from users to the H-AP. In this system, we aim to maximize the throughput by jointly optimizing the energy and information beam forming vector of H-AP. As the problem is non-convex, we first apply zero forcing method to cancel the self-interference at H-AP and then employ a series of efficient variable substitutions and a low-complexity algorithm to obtain the global optimum. Simulation results demonstrate that the proposed scheme can effectively improve the achievable throughput in the WPCN.

I. INTRODUCTION

The evolution of wireless communication networks with ever-increasing data traffic call for air interface enhancements to exploit the finite radio resources more efficiently. Future 5G networks are aimed to provide capabilities for very high achievable data rates, very low latency, ultra-high reliability, and the possibility to handle extreme device densities, in cost and energy efficient manner. In the full-duplex (FD), or more explicitly in-band full-duplex wireless (IBFD) transmission concept, a wireless terminal is allowed to transmit and receive simultaneously in the same frequency band. The concept sets high requirements to the transceiver implementation due to self-interference phenomena (i.e., transmit signal leaking into its own receiver), but when successfully solved, it provides significant improvements to wireless systems operation [1]. Enabling wireless devices to operate in full-duplex mode offers the potential to double their spectral efficiency in terms of transmitted bits per second per Hz. Full-duplex transmission can reduce air interface delays and facilitate improved collision detection/avoidance mechanisms on contention based networks.

In-band full-duplex wireless has a long history, and the concept has been utilized already in 1940s with full-duplex radars [2]. Terrestrial wireless communication systems like cellular mobile and WiFi have not yet largely utilized full-duplex transmission. In these systems, full-duplex has been used in some special cases, e.g., relaying applications [3]. However, interest in applying full-duplex to future evolution of wireless systems has risen significantly during past few years. Potential use cases proposed for full-duplex in the literature include relaying, self-backhauling, microwave backhaul links, mesh networks, cognitive radio, access points/base stations and devices in Wi-Fi and mobile systems [1][4]-[8].

The Full-Duplex Radios for Local Access - DUPLO project [9] is a research project within the Seventh Framework Programme for research and technological development (FP7) of the European Commission (EC). The DUPLO project is a concerted effort with partners from industry and academia that addresses the challenge of developing transceiver techniques and system level solutions for in-band full-duplex operation in small area radio systems. The project started in November 2012, and concludes in May 2015.

DUPLO has studied potential full-duplex transceiver techniques for compact radio devices such as small cell access points, tablets, smart phones, and smart glasses. Three RF/antenna design solutions for full-duplex radios have been developed, fabricated and validated. The first design is based on self-interference cancelling transceiver front-end structure [15]. The second design is an antenna technique based on dual-polarized microstrip patch antenna structure, complemented with an active analog cancellation network [13]. The third design is based on electrical balance duplexer circuit which connects with a single port antenna [13]. The DUPLO RF antenna solutions are designed with the aim to enable their integration into the compact radio device as a separate module, or on the radio chip (system on chip, SoC).

In that respect, DUPLO is in the leading edge in developing and presenting solutions for integrated design targeted specifically for in-band full-duplex operation [19][20][38].

As proof-of-concept for the functional operation, a short distance point-to-point link with two DUPLO full-duplex transceivers has been successfully demonstrated in VTC’2015 Spring DUPLO Workshop [11]. At system level, the DUPLO focus has been in small area radio systems. System level studies are conducted to evaluate attainable gains of using full-duplex transceivers in different network nodes and to study radio resource management and protocol solutions for networks deploying full-duplex transmission in the air interface. Key findings from conducted radio resource management and protocols studies are reported in multiple journal and conference papers [21]-[25].

This paper provides a summary on the main results of the technical work conducted in DUPLO WPs 1-6, and provides further conclusions on the potential and future development needs of in-band full-duplex transmission in wireless systems.  

II. CHALLENGES AND TECHNICAL APPROACH
The in-band full-duplex transmission scheme differs fundamentally from conventional duplexing schemes, i.e., frequency division duplexing and time division duplexing, which are used in legacy wireless communication systems. While the conventional duplexing schemes are based on orthogonal spacing of transmit and receive signals (either in frequency or time domain), the full-duplex concept enables a wireless terminal to transmit and receive simultaneously in the same frequency band. Full-duplex offers the potential to improve the radio system performance, but sets also challenges for wireless transceiver implementation as well as system deployment.

A. Full-duplex transceiver

Simultaneous transmission and reception at the same frequency band creates self-interference (SI) (transmit signal leaking into its own receiver, see Figure 1.) problem in the transceiver. The self-interference deteriorates receiver (RX) performance unless it is significantly reduced (ideally down to noise floor level). The total self-interference reduction requirement depends on the deployment scenario, and can be more than 100 dB to get full gain out of full-duplex transmission. To achieve this challenging requirement, the self-interference reduction needs to be implemented constructively in multiple stages across the full-duplex transmitter (TX) chain (antenna, RF, and baseband). Furthermore, these techniques should be self-adaptive to maintain the requirements over different propagation conditions and environments.

DUPL0 targets solutions for wireless radios to facilitate full-duplex operation in compact commercially attractive communication devices. The focus in RF/antenna circuit development is in solutions can offer substantial self-interference isolation or cancellation and can be integrated into the compact radio device as a separate module, or integrated on the radio chip. The full-duplex radio solutions presented in literature mainly rely on physical dimensions (i.e., antenna spacing) or require bulky components [10][4], hampering dense integration. The focus in digital baseband algorithm development is in search for efficient solutions to improve self-interference cancellation performance in the presence of transceiver non-linearity, channel estimation, and performance improvements with joint RF and digital cancellation.

B. System scenarios

DUPL0 full-duplex usage scenario in public safety networks consists of terminals operating in relaying mode forming UE relay connections and mobile ad-hoc network configurations. The basic set-up (Fig2-a) is the point-to-point connection between two nodes (either BS or UE types, or both). In this set up, the specific challenge with full-duplex transmission is the self-interference in each node. Depending on the link scenario, the transmit power level may range from roughly 80 dB to 120 dB stronger than the receiver noise floor, thus implying that the total self-interference reduction (isolation and cancellation) requirement should be on the same order [14].

Another potential usage scenario for full-duplex transmission is shown in Fig2-b, where the same spectral resource is simultaneously used for two connections; i.e., the BS is transmitting a signal to one UE while receiving another signal from another UE. In this case only the BS needs to be full-duplex capable device, while the UEs can be legacy half-duplex devices. Additional challenge in this case is the inter-node interference (between the transmitting and receiving UE). This calls for novel radio resource management solutions (e.g., scheduling, power allocation) to use available radio resources efficiently.

In multiple cell case, full-duplex operation creates interference paths between all active nodes as illustrated in Fig2-c. Thus, in network level, the full-duplex system implementation challenge is not only how to realize compact full-duplex device with high self-interference cancellation (SIC) capability, but also how to combat with additional inter-node interferences simultaneous transmission and reception causes to the system. Furthermore, in practice, the network level gain of full-duplex transmission depends on multiple aspects (traffic asymmetry, network architecture, propagation conditions, etc).
Another network configuration covered in the DUPLO project is mesh network, as illustrated in Fig3. DUPLO studies in this scenario are related to routing and protocol studies in IEEE802.11 technology based mobile ad-hoc networks deploying full-duplex nodes.

DUPLO has implemented a proof-of-concept hardware demonstrator to validate that the solutions developed in the project can be combined together as a complete and working full-duplex transceiver solution, operational on subset of system scenarios. The system set-up for the proof-of-concept consists of short distance wireless point-to-point connection between two full-duplex transceivers, see Fig4.

III. FULL-DUPLEX TRANSCIEVER

Full-duplex is a promising scheme in wireless communications to increase the spectral efficiency and/or throughput while improving the network fairness and coordination. Full-duplex is considered as a promising candidate to support the mobile network evolution towards 5G. The implementation of the full-duplex concept is, however, hampered by the limited capability of the radio transceivers to prevent receiver sensitivity degradation due to self-interference.

The self-interference caused by the different paths can be cancelled by copying reference signal(s) from the TX chain and subtracting reference signal(s) after modification in the RX chain. This modification involves attenuation and phase shifting to cancel the frequency-independent SI and additional signal delaying to cancel the frequency-dependent SI. As shown in bottom figure of Fig5, the SI cancellation can be realized from various points in the transmitter chain to various points in the receiver chain.

A. RF/analog and antenna solutions for full-duplex transceiver

One of the main objectives of the DUPLO project was to pave the way for the introduction of the full-duplex concept in short range wireless communication systems. Focussing on the RF/antenna/analog part of the full-duplex transceiver, different design requirements were targeted:

- compact in form-factor to support dense system integration
- implementable in low-cost scaled technology
- suitable for mass-production
- reconfigurable to support e.g. other operation frequencies or modes
- self-tuning with changing operation conditions or environmental conditions
- compatible with in-system and/or legacy components (e.g. commercial off-the-shelf components)

In DUPLO, different RF/antenna/analog solutions have been developed. These solutions cover 1) a SI-cancelling front-end, 2) a dual-polarized antenna structure and 3) an electrical balance duplexer as illustrated in Fig6. Although all these solutions target integration in compact radio units, they offer specific benefits and can thus be applied in different applications. The SI-cancelling front-end targets dense on-chip implementation suitable for mass-production and digital/analog/RF co-integration, and uses a dual COTS antenna structure with a moderate isolation between the antenna elements

B. Electrical balance duplexer

The antenna size is generally considered as one of the main bottlenecks for compact integration of FD radios. The electrical-
balance duplexer operation principle is illustrated in Fig7; the RF circuit comprises a hybrid transformer and a balance network which is essentially a tunable dummy load impedance. In case the dummy load impedance matches the antenna impedance, an “electrical balance condition” is achieved, virtually isolating the receiver from the transmitter. By virtue of this purely passive cancellation process, any noise and nonlinearity products generated in the transmitter are also cancelled in such electrical balance condition.

Fig7. Electrical balance operating principle illustrated on the first prototype for (a) TX operation and (b) RX operation: in FD, (a) and (b) occur at the same time and frequency

C. Digital baseband self-interference cancellation

A general block diagram for the digital cancellation is displayed in Fig8. Known transmitted data is used for SI channel estimation, the accuracy of which is relied on the self-interference-to-noise ratio. In a real scenario, self-interference channel includes multipath and it can change dynamically. To improve the estimation performance, coefficients for nonlinear models are estimated jointly with self-interference channel impulse response.

Fig8. Block diagram of the digital baseband self-interference cancellation

D. Subband approach for joint baseband-RF self-interference cancellation in full-duplex wideband transceiver

The performance of the full-duplex system can be degraded by the frequency selective transmit-receive path isolation in the full-duplex transceiver and also due to multipath in the SI channel. One solution to overcome this problem is an uneven SI cancellation over the received signal band, i.e. the frequency band is divided into several subbands and then SI cancellation is performed at each subband independent from other subbands. One realization for this solution is presented in Fig9, where the received signal is filtered to subbands, and then SI cancellation is performed at each subband independently.

Fig9. Block diagram for joint analog/RF and digital baseband SI cancellation

IV. FULL-DUPEX TRANSMISSION IN WIRELESS NETWORK

A. Full-duplex system performance

The reference scenarios are listed here first. It is worth noticing that the algorithms and protocols related to the assessed study cases are described in detail in another DUPLO WP4 deliverable

1) A point-to-point link is an essential unit and basic building block of many wireless networks. For example, in a wireless local area network (WLAN), every transmission between user devices and their access point (AP) can be regarded as a point-to-point link during the transmission period. Yet another example would be wireless backhauling in small cell deployments on mobile platforms such as trains, cars or airplanes.

2) Standalone small cell with a full-duplex base station serving multiple UEs which operate a) in half duplex mode or b) in full duplex mode. A typical realization of this use case could be a small cell deployed at home in e.g. residential area.

3) Multiple small cells with a full-duplex base station serving multiple UEs which operate a) in half duplex mode or b) in full duplex mode. A typical realization of this use case could be a small cell deployment in an office space, sports arena or shopping centre to name a few.

4) One considers relaying schemes, where a FD BS helps the communication between two UEs, as depicted in Figure 48. In this scenario, the FD BS implements cooperative protocols in order to help the communication between two UEs. This scenario may be used in coverage extension of networks.

5) Finally, scenarios IEEE 802.11 FD Mobile Ad-hoc NETworks (MANET) are investigated and the scenarios are typical for instance in future public protection and disaster relief (PPDR) systems

B. Radio resource management and protocols
Radio resource management in small cells

Radio resource management is a crucial point to consider in order to exploit full duplex as efficiently as possible. In DUPLO, we have considered several aspects of radio resource management in both single cell and multi cell deployments. Several algorithms have been devised in order to tackle problems such as spectral efficiency maximization, scheduling, co-channel interference, power allocation etc.

Single cell deployments

we have focused on co-channel interference from uplink UEs to downlink UEs connected to a same base station and have taken into account the effect of correlated shadowing. We have considered multiple half duplex UEs randomly scattered around a full duplex base station and have devised a procedure to derive the approximated distribution parameters of the received power from the desired transmitter as well as the co-channel interference at the user of interest thus making it possible to derive the distribution of the signal to interference ratio (SIR) which lead to an expression for the outage probability [28].

Multi cell deployments

In Fig10, we show a multi cell deployment scenario with multiple base stations and multiple UEs. A given user receives interference not only from neighbouring users but also from neighbouring base stations.

![Fig10. Illustration of a random deployment of small cells and user terminals over an arbitrary network area. Shaded squares represent user terminals, while shaded up-triangles depict small cell base stations. A heat map represents the corresponding random composite fading channel where the fading intensity varies from red/strong to dark blue/weak](image)

We have also considered the MIMO case in multi cell deployments. In this case, multiple antennas are used to serve multiple full duplex users from a full duplex base station as shown in Fig11

![Fig11. Full-duplex MIMO multi-cell system](image)

In order to solve the weighted sum-rate maximization problem to compute the optimum precoding vectors and the receiving vectors, we proposed a low complexity alternating algorithm which converges to a local optimum point [16].

Relaying

The topology in Fig12, shows a full duplex base station assisting in relaying data from one user to another user. In this context, we have studied two full duplex relaying schemes: full duplex dual hop (FDHD) and full duplex joint decoding (FDJD).

![Fig11. 3-node relaying setup: UE1 acts as a source and communicates to the destination, UE2, with help of a FD BS, which acts as a relay node](image)

In the first case, the direct link (source to destination) is seen as interference for the destination while in the second case, the direct link is seen as useful information and an iterative block decoding process is employed at the destination. We derived outage probability formulations in both cases [29].

MANET protocols

DUPLO system level studies have also focused on Mobile Ad-hoc Networks. In these types of networks, there is no central decision system (such as a base station or an access point) and information is usually relayed through several nodes before reaching the destination. Fig12 shows an example of such a network with multiple multi-hop transfers occurring.

![Fig12. Example MANET topology with multiple multi-hop](image)

Based on simulation results, we have seen that routing can also be optimized for full duplex MANETs but a substantial amount of control information would need to be exchanged between the different nodes in the network. This is why we have also proposed
a control plane design that takes a cross-layer approach in order to merge network and MAC layer information and aggregates control messages in order to have a better view of the topology whilst limiting the amount of control messages flowing through the network.

V. PROOF-OF-CONCEPT VALIDATION AND TESTING

A. Proof-of-concept demonstrator

DUPLO project has identified small cells as one of the main areas of interest for the project, due to their relevance for future 5G networks, as well as because small areas with short link distances and low transmission powers forms feasible deployment scenario for full-duplex technology. Due to these reasons, a small cell indoor scenario has been selected for the DUPLO proof-of-concept.

DUPLO WP5 showcases two DUPLO demonstrators which embed different DUPLO solutions. These DUPLO demonstrators are:

- Single-port antenna radio node demonstrator: This demonstrator comprises the electrical balance duplexer developed in DUPLO WP2 and the digital SIC algorithm developed in DUPLO WP3.
- Dual-port antenna radio node demonstrator: This demonstrator comprises the dual-polarized antenna and the active cancellation network developed in DUPLO WP2 and the digital SIC algorithm developed in DUPLO WP3.

Both demonstrators are able of adapting to the environmental changes close to the antenna by means of implementing automatic tuning algorithms over the analog circuitries. The radio nodes are completed with WARP version three radio boards [26] and WARPLab framework [27].

Single-port antenna radio node

The single-port antenna radio node also comprises digital SIC algorithms to further cancel the remaining SI. Fig13 shows a picture of the single-port antenna radio node:

1. WARPv3: WARP v3 has been used as the integration platform. WARP v3 is controlled by MATLAB via the Ethernet connection, as will be described later in this section.
2. Tunable electrical balance duplexer module: The tunable electrical balance duplexer is mounted on this module via direct chip bonding.
3. Power supply board: This power supply board has the ability to route and distribute different supply voltages by manual setting of the jumpers. Redistribution of the supply voltages is not needed. External power supply sources are connected to the power supply board.
4. Serial control module: The serial control module is a custom-designed PCB which enables communication from MATLAB to the shift register via USB. The serial control module performs the necessary data translation and takes care of the USB protocol.
5. Antenna: An antenna from a commercial USB WiFi module has been used. This WiFi module has been hacked to connect directly to the antenna itself, bypassing all the hardware on this WiFi module. The antenna has a planar inverted-F patch structure, and has only one radiation element and one connector port.

The self-interference isolation performance of the tunable duplexer is determined by how accurate the balance network impedance equals the antenna impedance. With this regard, an automatic tuning algorithm has been implemented in MATLAB to tune the EBD impedance over different operating conditions [18].

Fig13. Picture of the full-duplex single-port antenna radio node

The automatic tuning algorithm implemented for the electrical balance duplexer is executed in two main phases. The first phase is the training and modelling phase which gathers a data-set that describes the relation between the SIC and R/C codes during constant antenna impedance conditions. Fig14 (a) shows an example of the data-set gained from the training phase.

Fig14. (a) An example of the training data-set for the SIC versus R/C codes, (b) an example of the development of the angular search in terms of R and C codes.

Based on the obtained data-set a mathematical model is derived by fitting the theoretical equations that describe the circuit. During the second phase, the tuning is performed during system operation, when the balance network is tuned by estimating the difference between antenna and EBD impedance from applying the measured SIC in the model derived in the previous phase. But as the antenna impedance is a complex value, an angular search algorithm is required to determine also the phase of the difference between impedances to be able to use the model to find the required R/C codes. Fig14 (b) shows an example of the angular search implemented in the second phase of the tuning algorithm.
Dual-port antenna radio node
The active cancellation network uses variable amplitude and phase coefficients to cancel the self-interference leaking from the antenna. These coefficients must be dynamically tuned in order to adapt the cancellation signal to the wireless channel response, therefore, an automatic tuning algorithm is necessary to find the attenuator and phase shifter values which minimize the level of detected self-interference in an efficient way.

B. Validation and performance measurements
The DUPLO demonstrator has been evaluated in a wireless indoor environment with people and objects moving around the full-duplex radio transceiver. By doing so, the adaptability of the analog and digital cancellation blocks to the time varying wireless channel is demonstrated. Table 1 depicts the main features and technical details of the scenario used for DUPLO proof-of-concept validation.

Table 1. Specifications for DUPLO proof-of-concept

<table>
<thead>
<tr>
<th>Feature</th>
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<tbody>
<tr>
<td>Distance</td>
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</tr>
<tr>
<td>Carri er frequency</td>
<td>20</td>
</tr>
<tr>
<td>Signal</td>
<td>20</td>
</tr>
<tr>
<td>Type of Signal</td>
<td>OFDM based</td>
</tr>
<tr>
<td>Modulation Schemes</td>
<td>Up to</td>
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</table>

As can be seen, both WARP boards are connected to a control PC which comprises full-duplex baseband and digital cancellation block. Moreover, the EBD tuning is also implemented in this PC. The total self-interference cancellation provided by the single-port antenna radio node is 66 dB in 20 MHz of bandwidth. Fig15 shows a picture of the system setup including the wireless link.

Fig16 illustrates the system performance over different link distances (for a BPSK digital modulated signal with 0 dBm of WARP transmit power). These results show the EVM performance measured at both radio nodes when the nodes are operating in full-duplex or in half-duplex (noSI). It can be observed that the EVM performance during full-duplex closely matches with the half. The impact of the EBD linearity is illustrated in Fig17, where the relation between the EVM performance is illustrated in function of the WARP transmit power at a link distance of 60 cm. As in half duplex operation the EVM scales linearly with the transmit power, the communication link is not subjected to any nonlinear distortion. In full-duplex operation, this linear trend is also observed at low WARP transmit powers. However, when the WAPR transmit power exceeds 0 dBm, the full-duplex EVM performance degrades because the balance network starts to generate nonlinear distortion which directly couples to its own receive [12], and degrades the FD EVM performance. Given the expected losses in the EBD and the inter-connections, the difference between WARP transmit power and the power provided to the antenna equals about 6 dB. This limits the link distance obtained with this EBD prototype and with this experimental setup.

Fig17. Relation between the measured EVM performance and the WARP transmit power

The full-duplex baseband and digital cancellation block runs on the control PC, while it also sends the activation command via the serial port to the microcontroller when it is necessary to tune the active cancellation network, i.e. when analog SIC drops below 50 dB. Fig18 shows a picture of the evaluation setup for the dual-port antenna demonstrator.
VI. FUTURE ENHANCEMENT AND CONCLUSIONS

Compared to the state-of-the-art, the developed designs differ mainly in terms of form-factor and integration potential in compact or portable radio system devices. This is significant advance for the DUPLO solutions, since the previously published techniques mainly rely on physical dimensions (i.e. antenna spacing) and/or require bulky component. The DUPLO proof-of-concept hardware demonstrator integrates sub-set of the designs into a complete full-duplex transceiver solution enabling performance measurements in realistic dynamic indoor operation environment.

Transceiver design supporting flexible duplexing is also potential further research direction. The opportunity for full-duplex in larger form-factors should also be considered in relation with future 5G, for instance with connected cars. Furthermore, development of full-duplex techniques for multi-antenna systems is another potential research direction.

The results from conducted studies on full-duplex transceiver techniques and system level solutions are encouraging, and pave path for introducing full-duplex transmission as an air interface technology for future 5G systems. Obviously there are several further research opportunities and development needs remaining after the DUPLO project. For example, improving the performance of full-duplex transceiver designs for compact radio devices, integration of full-duplex with other protocols in the radio transceiver, full-duplex MIMO, and enhancements to radio resource management and protocols to improve system performance in multi-cell environments and in co-existence with half-duplex systems.

VII. REFERENCES


[27] https://warpproject.org/trac.
