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Adam Narbudowicz
Technological University Dublin, adam.narbudowicz@mydit.ie

Giuseppe Ruvio
Technological University Dublin, Giuseppe.Ruvio@tudublin.ie

Max Ammann
Technological University Dublin, max.ammann@tudublin.ie

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Passive Self-Interference Suppression for Single Channel Full-Duplex Operation

Adam Narbudowicz, *Member, IEEE*, Giuseppe Ruvio, *Senior Member, IEEE*, and Max J. Ammann, *Senior Member, IEEE*

***Abstract*—Full duplex radios have become a topic of increased interest in the wireless communications community. As part of this development, many efforts were directed to passively decrease the self-interference level at the antenna outputs. However, in many proposed solutions transmission and reception occur through different propagation channels. This paper demonstrates and quantifies the negative impact of channel differentiation on pivotal applications of full-duplex radio, such as cognitive radio. Antenna designs used for self-interference suppression in full-duplex radio architectures are analyzed. In order to ensure that transmission and reception occur within the same propagation channel, the use of the envelope correlation coefficient is proposed. The paper aims to firstly define the problem and proposes a metric to quantitatively assess full-duplex antenna designs. This is followed by analysis and discussion of representative full-duplex solutions (i.e. their antenna and passive RF feed components) proposed in the literature. Finally, it is demonstrated for the first time, that the passive non-magnetic self-interference suppression comes at the cost of increased losses in the structure. A theoretical upper limit for the antenna efficiency is proposed. Its consistency is verified for three representative full-duplex antenna designs which are highly documented in the literature.**

***Index Terms*—Full-duplex radio, self-interference suppression, antenna.**

INTRODUCTION

FULL DUPLEX radio systems, also called Simultaneous Transmit And Receive (STAR) radio systems, have gained strong attention in the last decade. Prior to this, the full duplex radio solutions required bulky and costly devices (e.g. ferromagnetic circulators), suitable for radar systems, but not for affordable handheld communication terminals. This situation changed recently with multiple technological advancements [1-8], allowing suppression of self-interference, the main inhibitor to full-duplex radios, while using miniaturized and affordable components. Most notably, the recent work by Reiskarimian and Krishnaswamy [1] introduced a transistor-based magnetic-free circulator that can be fully incorporated into an IC.

In order to achieve a sufficient level of self-interference suppression, it is commonly accepted that the system must combine multiple techniques at different stages of the communication chain – in both analogue and digital domains [2, 3]. Among those, passive cancellation by an antenna system has also been reported with numerous solutions benefiting from antenna and feed design [4 - 9]. The most efficient schemes propose to electromagnetically isolate the transmit and receive antennas [4 - 8] which heavily impact their radiation patterns and results in transmission and reception occurring within different propagation channels. This, as will be discussed in this study, can severely compromise some key applications of full-duplex radio.

In this paper, we analyze the suitability of antennas for full-duplex radio, i.e. their capability to suppress self-interference, for identical transmit and receive propagation channels. Currently, there are no metrics proposed to assess whether a system uses the same propagation channel for both transmission and reception. Assessing wireless systems solely with respect to increased information capacity is not sufficient, as there are other techniques – e.g. MIMO or diversity schemes – which allow similar (or even greater) capacity increase, while operating on completely different principles. Therefore the adoption of the Envelope Correlation Coefficient (ECC) metric is proposed here to separate MIMO-capable solutions from those capable of full-duplex operability. Furthermore, we demonstrate that it is impossible – using only passive, linear techniques - to simultaneously achieve good passive isolation, high efficiency and coherent transmit and receive patterns. An upper efficiency limit is finally proposed.

APPLICATIONS AND CATEGORIZATION

Full duplex radios offer up to a doubling in the communication capacity of wireless systems by simultaneous transmission and reception. In practice this factor will be further reduced, as many applications produce asymmetric traffic, i.e. download is much greater than upload or vice-versa. Given the expectations that the future 5G and Internet of Thing systems require almost exponential growth in data throughput, the 100 percent increase offered just by simultaneous transmission and reception seems negligible.

However, the true benefits of full duplex radios come with new possible applications they offer. One of them is cognitive

Adam Narbudowicz and Max J. Ammann are with Antenna & High Frequency Research Centre, Dublin Insititue of technology, Dublin 8, Ireland (e-mail: adam.narbudowicz@dit.ie).

Giuseppe Ruvio is with Antenna & High Frequency Research Centre, Dublin Insititue of technology, Dublin 8, Ireland and College of Engineering and Informatics, National University of Ireland Galway, Galway, Ireland.

radio, which attempts to re-use the parts of spectrum which are normally assigned to other systems but remain unused at a given time and place [10]. Simultaneous transmission and reception allows quick detection of unused spectrum bands, as well as rapid termination of the transmission if the primary user of the band activates. If the receive pattern of the secondary user has a null (i.e. angles from which the incoming signal cannot be seen by the antenna) in the direction of the primary user, it cannot detect its activation. However, if the transmitting and receiving patterns are different, it is possible that the secondary user signal will be still transmitted in the area of that primary user, causing interference. This problem remained unsolved in some early implementation of full-duplex radios [5].

Another possible application is to increase the privacy of wireless communication. This can be done by simultaneously receiving the meaningful communication, while transmitting a random noise signal [11]. The noise will bury the meaningful signal and make it indistinguishable to all other users. However if transmit and receive patterns are different, a potential eavesdropper can separate the noise from the communication.

It is also worth mentioning that theoretically a perfect isolation can be achieved with a passive multi-antenna system that exhibits orthogonal radiation patterns, e.g. where the null direction in one pattern corresponds to direction of maximum radiation/reception in the other and vice-versa; or when two orthogonal polarizations are used [8]. The use of orthogonal patterns, although capable of very good passive self-interference suppression, will further exacerbate the problem of blind-spots.

Based on physical phenomena used, the currently implemented techniques for passive self-interference suppression can be broadly divided into four vast categories:

- **Path-loss based,** where the suppression occurs in the antenna's far-field. This is the simplest and historically the first technique. It uses large separation between transmit and receive antennas [2], with the suppression facilitated dominantly by the path-loss effect. To avoid coupling the antennas should be placed in their far-field (preferably) or non-reactive near-field. Such spacing necessitates large transceiver dimensions, making the technique of limited use for modern radio devices, where the size reduction is of key concern.
- **Radiation-pattern based**, where the suppression occurs in the antenna's near-field. Advancement as compared to the previous technique, it is probably the most commonly used technique. It achieves suppression by differentiating the radiation patterns of transmit and receive antennas. This can be executed in multiple ways: by using directional antennas facing different direction [4]; by using two orthogonal polarizations [8]; or by other technique where coupling near-field effects are used [5]. Although seemingly different, all of them – including [5] which will be studied in more details below – achieve suppression by differentiating transmit and receive patterns. As described above this can lead to complication with certain applications (e.g. cognitive radio).
- **Circuit based**. Unlike in the previously described categories, the main suppression does not occur through radiating mechanism, but in the passive and linear high-frequency circuit. This allows greater miniaturization, as the bounded signal can be easily controlled. An example of such technique is [9] and will be studied in more details in below, using *Antenna II* and *III*.
- **Magnetic based**. A non-linear behavior of magnetic-based passive components (mainly circulators) can be used to achieve self-interference suppression. Due to the characteristics of magnetic materials, such devices are typically bulky, heavy and expensive. They find a common usage in large-scale radar systems (where such disadvantages are negligible) but not in compact radio devices. Such magnetic components are typically passive but not linear and therefore analysis techniques described below are not applicable to them. Due to their limited usage for compact radio nodes they are out of the scope of this paper and are only mentioned here for completeness.

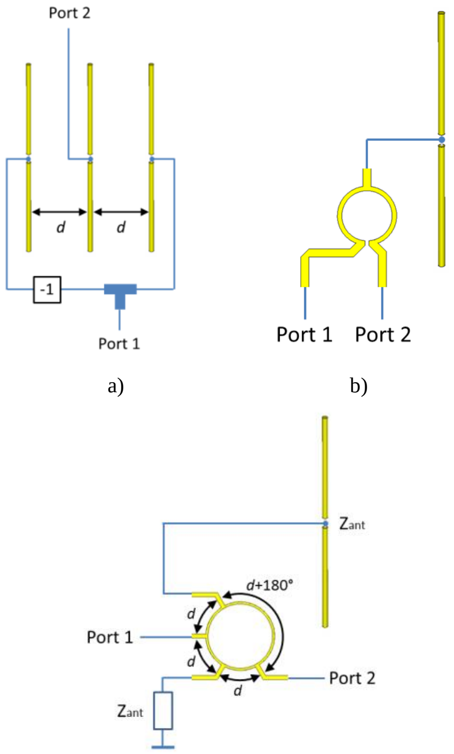
ENVELOPE CORRELATION COEFFICIENT

In contrast to full duplex, MIMO systems typically aim to diversify radiation patterns at inputs/outputs as much as possible in order to provide less correlated communication channels. A routinely used metric in MIMO systems is the Envelope Correlation Coefficient (ECC), which expresses the correlation of two radiation patterns (including polarizations) integrated over a full sphere. If the radiation patterns are the exact same, the correlation coefficient would be 1. If they are completely independent, the correlation would be 0. The same metric can be also used for full-duplex radio, for which case it will take the form:

$$\rho_{ECC} = \frac{\iint P_{RX}(\theta,\phi) P_{TX}^{*}(\theta,\phi) d\Omega}{\sqrt{\iint P_{RX}(\theta,\phi) P_{RX}^{*}(\theta,\phi) d\Omega \iint P_{TX}(\theta,\phi) P_{TX}^{*}(\theta,\phi) d\Omega}} \quad (1)$$

where P_{RX} and P_{TX} are respectively the receiving and transmitting radiation patterns, and $d\Omega$ is an infinitesimal solid angle, which is being integrated over the entire full sphere.

To maximize capacity for standard diversity/MIMO systems ρ_{ECC} should be kept as small as possible, optimally reaching zero. On the contrary, for full-duplex radios - due to problems described above - antennas should exhibit ρ_{ECC} as large as possible, optimally reaching unity. This would mean the transmission and reception radiation patterns are identical, including their polarizations.



a) b)

c)

Fig. 1. Three investigated cases of antenna systems with passive self-interference suppression: a) *Antenna I*; b) *Antenna II*; c) *Antenna III*.

CASE STUDY

To demonstrate the concept in practice, three types of antennas, already reported in the literature, are analyzed for successful passive self-interference suppression. All antennas were simulated using CST Microwave Studio 2016 [12], which is considered a state-of-the-art full-wave simulator for electromagnetic problems. All radiating structures (i.e. dipole antennas) are simulated using full-wave simulation in free space with the time domain solver. All circuit components are connected to radiators using CST Design Studio functionality. *Antenna I* uses an idealized lossless power divider, provided in the CST library and the signal inversion is realized by interchanging the “hot” and “ground” wires in a balanced antenna. The Wilkinson power divider in *Antenna II* and rat-race coupler in *Antenna III* were designed in CST Microwave Studio according to the state-of-the-art procedure in [14] and simulated using the time domain full-wave solver. The obtained S-matrices were connected with radiators and other components using CST Design Studio. The Z_{ant} impedance in *Antenna III* was extracted directly from the radiator S-matrix. The models are available online at charlie.electronics.dit.ie/node/541. As the study focuses on passive self-interference suppression, no active or digital components are used. However, any active technique described in the literature can be added as a subsequent block without causing loss of performance.

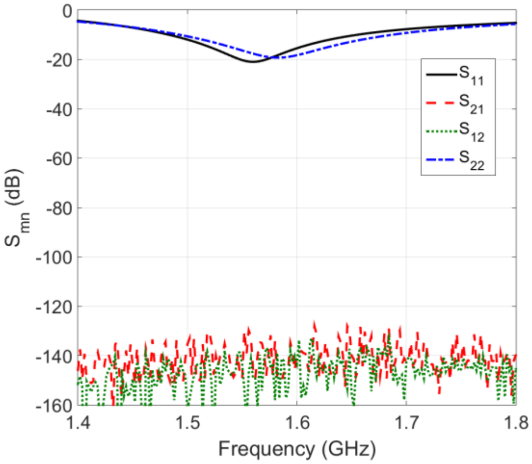


Fig. 2. Reflection and coupling of the two-port *Antenna I*.

The investigated antennas are considered to be representative to the range of solutions for passive self-interference suppression: starting from early attempts that are lossless but use different transmit and receive radiation patterns (*Antenna I*), followed by two solutions that use the same radiation patterns (ρ_{ECC} = 1) but generate losses. To the best of our knowledge there is no passive and non-magnetic solution that is both lossless and offers the same radiation patterns for transmission and reception. Furthermore, it is later argued that such a solution is physically impossible.

A. *Antenna I: lossless - uncorrelated patterns*

Fig. 1a shows a more wideband version of the scheme originally proposed in [5]. It involves three antennas located along a line. The antennas are equally spaced and connected with port 1 (assume receiver) via a lossless power divider. The signal from one antenna is inverted (i.e. multiplied by -1) corresponding to a broadband 180° phase shift. The remaining middle antenna is connected directly to port 2 (assume transmitter). Since the outer antennas are fed with a respective 180° phase shift, the signal will vanish due to destructive interference in the plane equidistant to both. Since the transmit antenna (port 2) is located in this plane, a strong self-interference suppression is achieved.

Fig. 2 shows the S-parameters at the ports in the proposed scheme, where S_{21} and S_{12} are transmission coefficients (inverse of isolation) for signals respectively: incoming from port 1 into

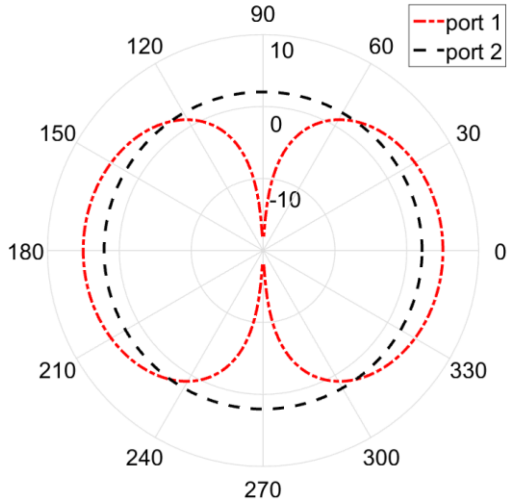


Fig. 3. Radiation patterns in horizontal plane for *Antenna I*.

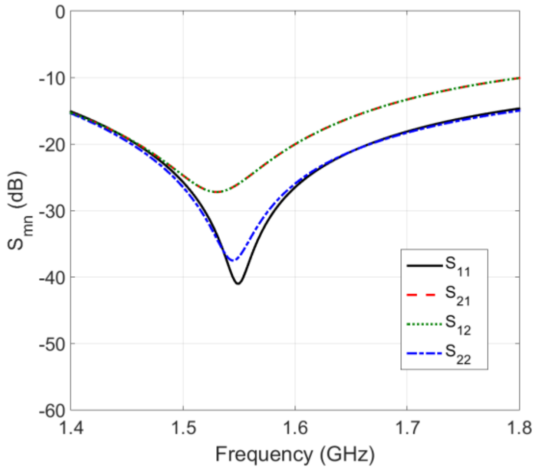


Fig. 4. Reflection and coupling of the two-port *Antenna II*.

port 2 (S_{21}) and from port 2 to port 1 (S_{12}). It can be seen that the scheme provides very strong self-interference suppression (below 120 dB), with signal leaking from transmit to receive ports at numerical noise level. Although it is expected to be worse in a practical implementation (e.g. due to the manufacturing inaccuracy in the distance between antennas), it can still offer very good performance. Since the design eliminates all wavelength-dependent components, the suppression is uniform within the whole antenna bandwidth. For the studied dipole case, it is 170 MHz, as compared to 5 MHz investigated in [5].

The solution is practically lossless, as the total calculated efficiencies (i.e. including mismatch losses) seen from port 1 and 2 are respectively 91 and 98 percent. However, the price to be paid is the low correlation of radiation patterns. As seen in Fig. 3, the antenna radiates and transmits in different directions, thus ρ_{ECC} = 3e-8, as calculated with (1) in CST Microwave Studio [12]. If the deep null in the receive pattern (seen in Fig. 3 for red dot-dashed curve at 90° and 270°) is directed towards the primary user, the system is blind for the activation of this user, while still transmitting a signal in its direction (black dashed curve in Fig. 3). This demonstrates the drawback of passive suppression: although the antenna is perfectly capable of increasing data throughput (i.e. with MIMO scheme), it is not the best choice for cognitive radio or security application as proposed in [10-11].

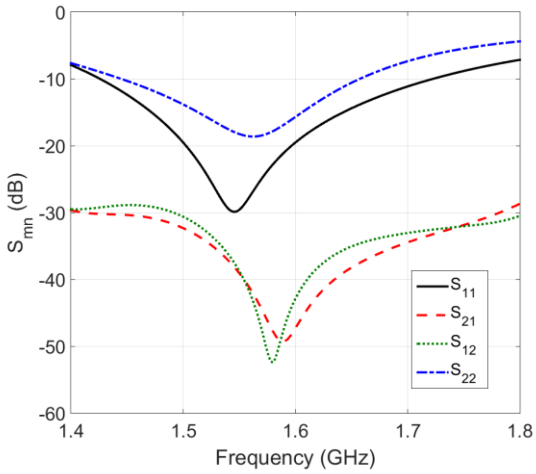


Fig. 5. Reflection and coupling of the two-port antenna III.

B. Antenna II: lossy - same patterns

Antenna II – as seen in Fig 1b - was first introduced in [13] to illustrate the problem of correlated losses in MIMO antenna systems. It consists of a single antenna, connected to two different ports via a Wilkinson divider. Such a divider is a routinely-used structure providing good isolation between two ports feeding the same antenna [14]. To achieve good isolation it has to incorporate a lossy element, here a 100 Ω resistor, where undesired energy is dissipated.

Fig. 4 demonstrates the simulated S-parameters of the antenna. The isolation is up to 27 dB, which is significantly less than what achieved with *Antenna I*. Since the signals are physically transmitted and received by the same radiator, it is inherent that the transmit and receive patterns are identical (ρ_{ECC} = 1). However, this configuration suffers from poor efficiencies due to the incorporation of a lossy resistor, which causes 3-dB (50 percent) loss. Thus efficiencies at both transmit and receive ports were calculated as 47 percent.

C. Antenna III: lossy - same patterns

The third scheme for self-interference suppression is the most advanced one and it was proposed in [9]. It consists of an antenna and an adaptive load, as seen in Fig 1c. It is assumed that the load perfectly mimics the antenna's impedance. Although in practice this is a very challenging task, for the purpose of our study we assumed this is perfectly executed.

To achieve good isolation the signal incoming from port 1 (assume transmitter) is divided into two branches. One goes towards the antenna, whereas the other one is connected to the adaptive load. Both the antenna and the load are also connected to the port 2 (assume receiver) with transmission lines that enforce a 180° phase shift between them. If the adaptive load is exactly the same as the antenna's impedance, the leaked signals at both paths are also the same. Due to the 180° phase shift a destructive interference is created, which strongly suppresses the leaked signal at port 2. On the other hand, any received signal will originate only from the antenna (and not the load), thus avoiding interference and feeding the signal towards the receiver (port 2). In our study the feed network as described above was integrated with a rat-race coupler – a routinely used and well known microwave device [14].

As seen in Fig. 5, the antenna offers good isolation between 30 and 50 dB, which is a significant improvement compared to *Antenna II*. This compares to similar isolation between 30 and 60 dB reported in [9] for the passive case. The problem of transmission and reception into different channels is nonexistent as again both mechanisms use the same radiator (ρ_{ECC} = 1). However, due to the presence of the additional load the antenna's efficiency is 49 percent at both ports. This indicates that similar to *Antenna II*, half of the power is lost. Although the rate of lost power in this configuration may seem high, in fact it will be demonstrated in the subsequent section, that this is the most efficient achievable option if one desires to use identical radiation patterns for transmission and reception, while benefiting at the same time from passive non-magnetic self-interference suppression.

Please also note that replacing the load with a real antenna would result in a more sophisticated version of *Antenna I*, doubling the efficiency at the cost of radiating and transmitting in different directions.

PASSIVE AND LOSSLESS SUPPRESSION

Hallbjörner in [15] demonstrated, that for a passive linear antenna systems there exists a dependency between correlation of radiation patterns, expressed as ECC in (1), and S-parameters. This can be denoted as:

$$0 = \frac{S_{11}S_{12}^{*} + S_{21}S_{22}^{*}}{\sqrt{\left(1-|S_{11}|^2-|S_{21}|^2\right)\left(1-|S_{11}|^2-|S_{12}|^2\right)}} + \\ + \rho_{ECC}\sqrt{\eta_1\eta_2} + \rho_{loss}\sqrt{(1-\eta_1)(1-\eta_2)} \qquad (2)$$

where ρ_{ECC} is the ECC as calculated in (1); ρ_{loss} is the loss correlation, i.e. proportion of losses that occur simultaneously in both antennas, and takes values between 0 and 1; η_N is radiation efficiency seen at *N-th* port (in our case either transmit or receive port).

S_{11} and S_{22} denote reflection coefficients at respective ports 1 and 2, i.e. a complex value whose amplitude is square root of power rejected at this port. In our study this includes effects of both antenna and all passive feed circuitry as depicted in Fig 1. For a typical antenna system the value is expected to be at least -10 dB or preferably lower.

For good self-interference suppression one needs high port-to-port isolation. Since the amplitudes of S_{21} and S_{12} are transmission coefficients, one requires those values to be as low as possible, preferably zero. For this case, the first term in (2) vanishes. Given this, for a lossless antenna system (i.e. $\eta_1 = \eta_2 = 1$), the equation can be satisfied only if $\rho_{ECC} = 0$, i.e. only when transmit and receive radiation patterns are orthogonal to each other.

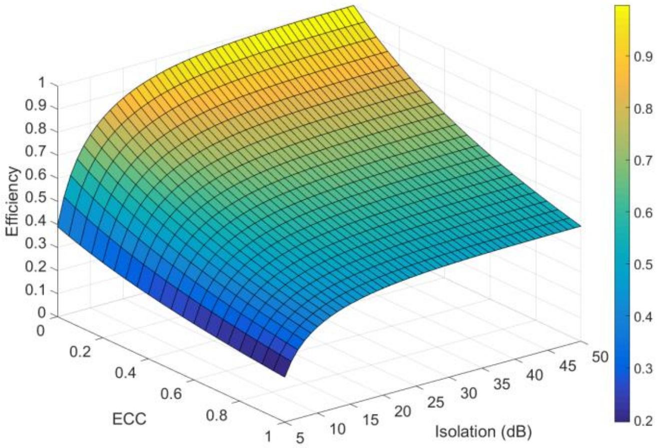


Fig. 6. Achievable efficiency for a passive self-interference suppression circuitry, as calculated from (2).

Fig. 6 demonstrates efficiencies of a system, calculated from (2) as a function of isolation and pattern correlation (ECC). It assumes typical realizable antenna parameters, that is: $S_{11} = S_{22} = -10dB$; $\eta_1 = \eta_2$; and $\rho_{loss} = -1$, which is the most optimistic case for efficiency.

The highest achievable efficiencies are seen when the radiation patterns are uncorrelated. However, this causes many disadvantages for full-duplex, especially when used for cognitive radio. On the contrary, if transmission and reception occur with the same patterns (ECC = 1) the maximum efficiency limit is 0.5. This limit does not change with S_{11} or S_{22} and only further decreases with $|\rho_{loss}| < 1$ (plots not shown for brevity).

Leaving aside the exact measurement of $|\rho_{loss}|$, it is known that it cannot exceed unity, as this would violate the energy conservation law. Thus (2) can be easily transformed to deduce the upper efficiency limit on passive suppression for full-duplex radio, where:

$$\frac{\sqrt{\eta_1\eta_2}}{\sqrt{(1-\eta_1)(1-\eta_2)}} \leq 1 \qquad (3)$$

In particular, if efficiencies of both antennas are the same, the maximum possible efficiency (with simultaneous good isolation and coherent transmit/receive radiation patterns) is 50 percent. This is consistent with Fig. 6 and seen for many realized passive suppression schemes (e.g. [9]).

CONCLUSIONS

The paper discussed general capabilities of various antennas for self-interference suppression, as required in full-duplex radio. Two main new findings were reported.

Firstly, the paper discusses the problem of a cognitive radio, which uses full-duplex with transmission and reception into different channels (i.e. radiation patterns). To systematically assess this problem, we propose to use the Envelope Correlation Coefficient. Contrary to MIMO systems, for full-duplex radio ECC = 1 is preferred.

Secondly, we use the methodology proposed in [15] to calculate the physical limitations on passive self-interference suppression. Most notably, we have demonstrated that it is impossible to have simultaneously a lossless antenna, good passive self-interference suppression and identical radiation patterns for transmit and receive. This shines a new light on antenna designs for full-duplex radios. However, this intrinsic trade-off does not affect self-interference suppression which is realized in the digital domain or using active components, as proposed in [1]. Unlike efficiency and radiation patterns, the self-interference suppression can be improved in subsequent non-passive stages of the transceiver. Therefore for cognitive radio implementations we would advocate antenna designs with high efficiency, ECC close to unity and poor isolation, while relying on non-passive techniques for self-interference suppression.

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BIOGRAPHIES

Adam Narbudowicz [S’12, M’14] (adam.narbudowicz@dit.ie) received Ph.D. in 2013 from Dublin Institute of Technology, Dublin, Ireland and M.Sc. in 2008 from Gdansk University of Technology, Gdansk, Poland. In 2014 – 2016 he was a postdoctoral research fellow at Institute of High Frequency Technology, RWTH Aachen University, Aachen, Germany. He is currently an EDGE Research Fellow at CONNECT Research Centre in Dublin Institute of Technology, working primarily on wireless physical-layer security for Internet of Things. He has (co-)authored some 50 scientific publications in peer-reviewed journals and conferences. His research interest are wireless physical-layer security, remote sensing, electrically small antennas and microwave circuitry for full-duplex radios. He is recipient of 2012 DIT Inventor Competition Award for the Best Postgraduate and Staff Invention and 3rd prize for Best Paper Award at ISAP 2017: International Symposium on Antennas and Propagation.

Giuseppe Ruvio [M’07, SM’15] (giuseppe.ruvio@dit.ie) completed a Specialist Master of Management in Clinical Engineering in 2017 from the University of Trieste, Italy, a Ph.D. on Microwave Engineering in 2009 from the Dublin Institute of Technology (DIT) and a Laurea degree from the University of Siena, Italy, in 2002. His recent research focuses on advanced antenna engineering, breast cancer microwave imaging, tissue-mimicking material engineering and dielectric properties measurement of biological tissues. He is currently lead electronic engineer in a commercialization project on microwave ablation. Dr Ruvio is IEEE Senior member and sits in the management committee of three COST Actions. He was awarded the Best Presentation Prize conferred by Bell Labs at the CTVR Conference 2012; the 2009 Hothouse Commercialization Prize, the 2008 CST University Publication Award and the 2006 best paper prize at the Loughborough Antennas and Propagation Conference.

Max Ammann [M’96, SM’08] (max.amman@dit.ie) is Director of the Antenna and High Frequency Research Centre, School of Electrical and Electronic Engineering, Dublin Institute of Technology. He spent eight years on radio systems engineering and antenna design for TCL/Philips Radio Communications Systems, Dublin. His research interests broadly include electromagnetic theory, antenna miniaturization for terminal and ultra wideband applications (UWB), antennas for medical devices and the integration with photovoltaic systems. He has in excess of 200 peer-reviewed papers published in journals and international conferences. He is a member of the EurAAP working group on Small Antennas and his team received various best paper awards at international conferences on Antennas and Propagation and several commercialization awards. As a member of the IEEE International Committee for Electromagnetic Safety, he participated in the revision of the IEEE Std. C95.1, 2005 standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz. He chaired and organized special sessions on small antennas, UWB antennas and UWB Wireless Communication Systems at EuCAP and IEEE APS & VTC. He is currently associate editor for the IEEE Antennas & Wireless Propagation Letters.