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Electrical Balance Duplexing for Small Form Factor Realisation of In-Band Full-Duplex

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1 Abstract

Transceiver architectures utilizing various self-interference suppression techniques have enabled simultaneous transmission and reception at the same frequency. This Full-Duplex wireless offers the potential for a doubling of spectral efficiency, however the requirement for high transmit to receive isolation presents formidable challenges for the designers of full duplex transceivers. Electrical Balance in hybrid junctions has been shown to provide high transmit-to-receive isolation over significant bandwidths. Electrical Balance duplexers require just one antenna, and can be implemented on-chip, making this an attractive technology for small form factor devices. However, the transmit-to-receive isolation is sensitive to antenna impedance variation in both the frequency domain and time domain, limiting the isolation bandwidth, and requiring dynamic adaptation. Various contributions concerning the implementation and performance of Electrical Balance duplexers are reviewed and compared, and novel measurements and simulations are presented. Results demonstrate the degradation in duplexer isolation due to imperfect system adaptation in user interaction scenarios, and requirements for the duplexer adaptation system are discussed.

2 Introduction

Demand for wireless communication services continues to grow at an astonishing rate. Although in many countries additional spectrum is becoming available (for example through the Digital Television switchover and the forthcoming release of military spectrum), and research into millimetre wave technology promises to exploit underutilized spectrum at much higher frequencies, this growth in available spectrum pales in comparison to the increasing demands of our connected future. Spectral efficiency will continue to be a key research driver for many years to come.

Radio systems typically require transmit signal powers which are many orders of magnitude higher than the receive signal powers (often by over 100dB). Due to this basic property, it has long been held that a radio system cannot transmit and receive on the same frequency at the same time, as the higher powered transmit signal would cause *self-interference* at the receiver, thereby obscuring the receive signal and preventing its reception. This limitation arises from the simple fact that wireless signals attenuate quickly with distance, and until now this has prevented the realisation of In-Band Full-Duplex radio (IBFD). In contrast, signals propagating through wires suffer comparatively little attenuation, and IBFD has been commonplace in wired telephony for over 100 years [1].

Today's radio systems achieve duplex operation by simply circumventing this problem. Uplink and downlink channels are separated in time, using Time Division Duplexing (TDD), or in frequency, using Frequency Division Duplexing (FDD), thereby avoiding co-channel self-interference. However, since the 1980s [2], [3], and particularly in recent years [4], research has successfully challenged the traditional duplexing paradigm, proposing new system architectures utilizing various techniques to provide high levels of transmit to receive isolation, thus allowing simultaneous transmission and reception at the same frequency. This has obvious benefits for spectral efficiency, theoretically providing double the capacity over TDD or FDD systems without increasing bandwidth.

To achieve in-band full duplex operation, the transceiver system must somehow supress the self-interference to an acceptable level. If the self-interference can be reduced to 6dB or more below the receiver noise floor, then the degradation in SNR due to the self-interference will be less than 1dB, and the bandwidth efficiency of the two way radio link is almost doubled. In Wi-Fi systems, this means that around 115dB of self-interference suppression is required. For LTE, which operates over longer ranges (and hence has a larger gap between transmit power and sensitivity), the requirement is higher, at around 123dB. As engineers we are, of course, quite familiar with using decibels, however it worth reflecting on the magnitude of this number: 123dB of interference suppression means that the interference must be reduced by a factor of over 1 trillion. It is little wonder that until recently in-band full-duplex has been assumed impossible.

3 Self-interference Suppression

To achieve these high levels of transmit-to-receive (Tx-Rx) isolation, various methods must be employed to supress the self-interference. Analog and digital cancellation techniques are key enabling technologies for IBFD systems [4], whilst antenna based isolation techniques provide passive isolation by exploiting signal directionality at the antenna port [5], [6], or by using separate antennas for transmitting and receiving [3], [7]. Antenna separation architectures utilise separate transmit and receive antennas, and can exploit directional antennas and shielding to improve isolation [7]. Whilst this can be extremely effective, the isolation is fundamentally limited by the physical separation of the antennas. For the antenna separations possible in basestation applications, high passive isolation of up to 71dB has been reported [7], however, for smaller antenna separations, the achievable isolation is significantly lower at around 30dB [3], [8]. This isolation could also be compromised by interaction with the users hand [8], and the now common requirement for MIMO would further increase the number of antennas, and hence the size of the device. Consequently, antenna separation architectures may not be an attractive option in smartphone and tablet devices, where size and form factor often take precedence over other design considerations. Similarly, single antenna architectures utilising circulators [5] are also unattractive for mobile device applications due to their size, cost, and limited isolation (approximately 15dB).

In this article we present an *alternative* antenna based isolation architecture, based on *Electrical Balance* in hybrid junctions, which can provide high transmit-to-receive isolation, but uses just a single antenna and can be implemented on-chip making it suitable for use in consumer mobile devices.

3.1 Electrical Balance in Hybrid Junctions

Electrical balance duplexing is by no means new, but has been used since the early days of wired telephony [1]. In a telephone system, the microphone and earpiece must both be connected to the telephone line, but must be isolated from one-another to prevent the users own speech deafening them to the much weaker incoming audio signal. This was achieved using a hybrid junction connected as shown in fig. 1.(a).

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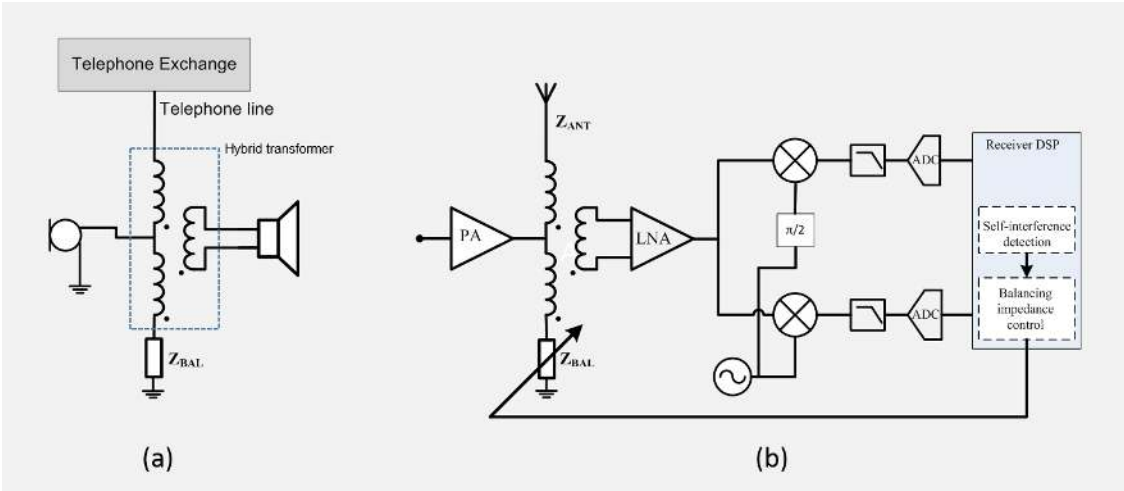

Figure 1. a) Electrical balance duplexer used to isolate the microphone and earpiece in a pre-electronic telephone. b) Electrical balance duplexer in a wireless transceiver including adaptive balancing impedance control.

The hybrid junction (also known as a "hybrid coil", "hybrid transformer", "bridge transformer", "magic tee", or simply a "hybrid") is a four port lossless reciprocal network in which opposite pairs of ports are isolated from one-another [9]. Its operation is depicted in Fig. 2.(b): assuming all ports are terminated with the correctly matched characteristic impedance, a signal arriving at any one of the hybrid's ports is divided between the two adjacent ports, but not coupled to the opposite port; the opposing ports are *conjugate*. This property of "Electrical Balance" can be exploited to isolate transmitter and receiver circuitry, but allow use of a shared propagation medium. The wireless duplexing application [6], [10], [11] is entirely analogous to the telephone duplexer, but substitutes the microphone, earpiece, and telephone line with the transmitter, receiver, and antenna respectively, as shown in Fig. 1.(b).

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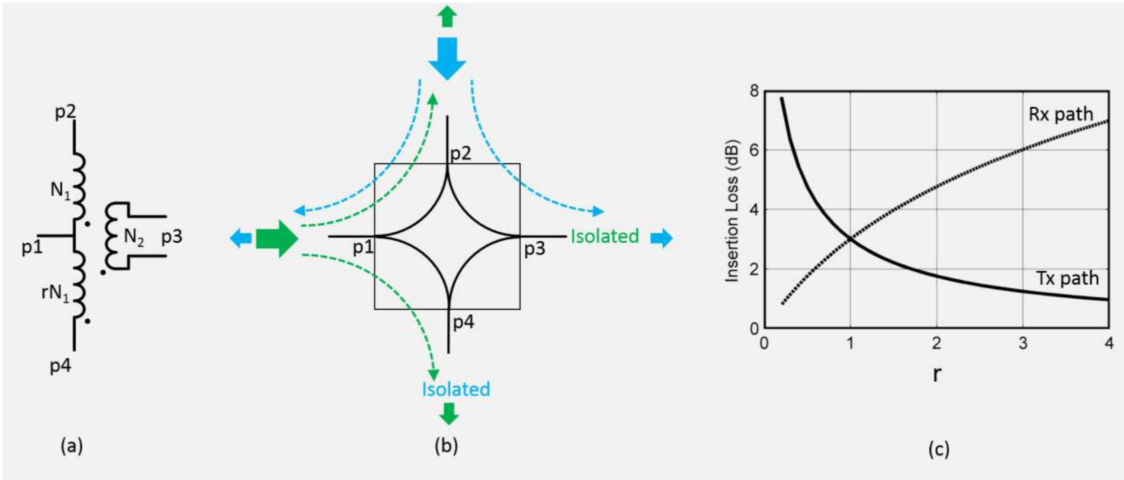

Figure 2. a) A hybrid transformer with tapping ratio, r**.** *b) Circuit symbol for a generic hybrid junction. The port numberings (p1-p4) correspond to Fig. 2.a and annotations show the signal coupling behaviour of a hybrid junction: adjacent ports are coupled and opposite ports are isolated from one another. c) Trade-off between Tx and Rx insertion loss, as controlled by the tapping ratio.*

In a wireless electrical balance duplexer the transmit current, supplied by the Power Amplifier (PA), enters the hybrid at the center tap of the primary winding (as shown in Fig. 1.b) and is split between two paths flowing in opposite directions, with one component flowing to the antenna (and being transmitted), and the other to the *balancing impedance*. The relative magnitudes of these currents is determined by the transformer tapping ratio, *r*, and by the values of the antenna and balancing impedances. The balancing impedance is adjusted such that these two currents create equal but opposite magnetic fluxes that cancel, and therefore zero current is induced in the secondary winding of the transformer - the receiver is isolated from the transmitter. A signal received at the antenna, however, causes currents to flow through the primary winding in the same direction, thereby coupling it to the receiver winding. There is, of course, some inherent loss associated with the duplexer's operation. Some of the transmit power is dissipated by the balancing impedance, and not all of the power received at the antenna is coupled to the receiver. These losses depend on the tapping ratio, and can be traded off against one-another by using a hybrid which is skewed in favour of the transmit or receive path, as shown in Fig. 2.(c). This relationship between the losses in the transmit and receive paths results from the reciprocity of the hybrid junction. For example, if the circuit were designed to deliver all of the transmit power to the antenna then, since the circuit is reciprocal, all power arriving at the antenna would be delivered back to the transmitter (and therefore not to the receiver). Consequently, for the system to function in both transmit and receive modes, there is some unavoidable loss, which for a symmetrical hybrid (i.e when r = 1), is 3dB in both the transmit and receive paths, reducing the transmitter efficiency and receiver sensitivity. Fortunately, however, these losses can be reduced by employing a *noise matched* receiver design.

3.2 Noise Matching

It is possible to mitigate the RX insertion loss of the duplexer by noting that the absolute power of the receive signal is not the parameter that should be maximised; it is only the SNR of the receive signal that is important. Therefore, instead of maximising power transfer between the antenna and the Low

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Noise Amplifier (LNA), it is better to design the duplexer to maximize the voltage gain experienced by the receive signal, and thereby minimise the receiver noise figure. This *noise matching* technique is possible because the receiver SNR depends not only on the receive power, but also on the impedance matching between the LNA and the various thermal noise sources in the duplexer circuit. To minimize the noise figure, the LNA input impedance is deliberately mismatched, thus reducing power transfer, however the reduction in the noise power transferred to the LNA is greater than the reduction in the wanted signal power, and therefore the SNR is increased. In [11], an EB duplexer with noise matched LNA was fabricated and measured. This duplexer design skewed the hybrid to favour the transmission of power between the PA and the antenna, reducing the Tx insertion loss to 2.2dB. The resulting RX insertion loss of approximately 4dB was circumvented through noise matching, thus reducing the LNA noise figure to less than 1dB (as compared to 3dB for an impedance matched LNA), and giving a total receiver noise figure of 5dB. The Tx insertion loss and Rx noise figure of a noise matched EB duplexing transceiver is thus comparable to that of alternative architectures, such as the splitter, circulator, and coupler used for analog cancellation in [5]. A detailed example of noise matching in EB duplexers can be found in [10].

4 Differential and common mode architectures

The self-interference arriving at the LNA inputs can be divided into two signal modes. Common Mode (CM) signal components appear at the LNA inputs with the same phase at each terminal, whereas Differential Mode (DM) components appear in antiphase. In this system, the LNA is a differential amplifier, and consequently the CM signals are rejected and do not cause and self-interference further down the receive chain. It is therefore the DM isolation of the EB duplexer which determines the level of the self-interference suppression. However CM coupling must also be considered due to the high voltage swings which it may present to the LNA input. At all but low transmit powers, these CM Tx signals may be large enough to destroy the LNA circuit, and therefore to enable the transceiver to operate at practical transmit powers the EB duplexer must isolate the receiver from both DM and CM signals.

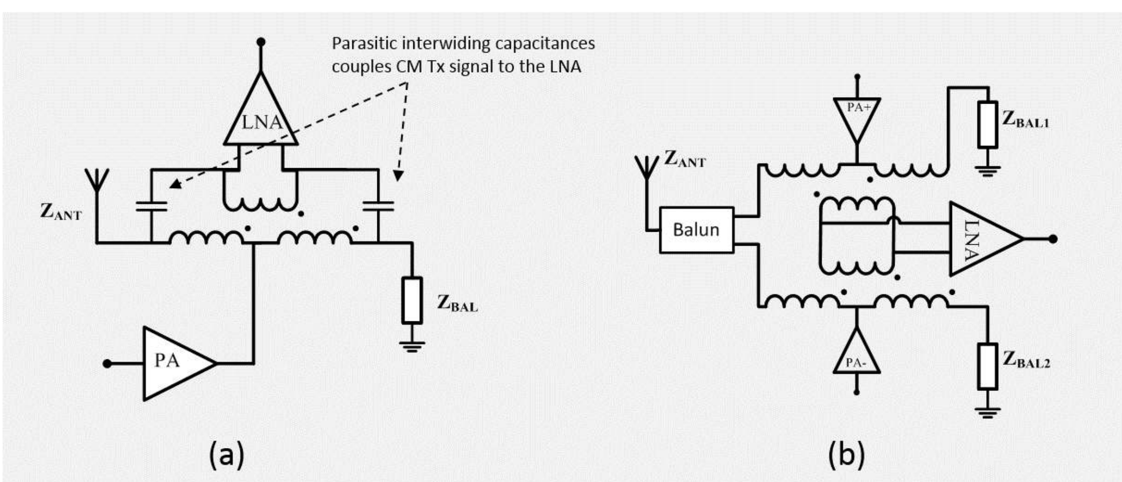

Figure 3: a) Single ended EB duplexer with parasitic interwinding capacitances causing unwanted CM coupling of Tx signal. b) Fully differential EB duplexer providing high DM and CM isolation.

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The duplexer depicted in Fig. 1.b theoretically provides infinite CM isolation [11], however in the practical circuit, parasitic capacitive coupling between the primary and secondary windings of the transformer (Fig. 3.a) results in significant CM coupling between the PA and LNA. The solution to this problem was proposed in [10], where a fully differential EB duplexer is introduced. In this circuit, a differential PA is used to drive two hybrid transformers. The receiver windings of these hybrids are then connected to the LNA in parallel, and since the input signals to the two hybrids are in antiphase, the CM coupling from each cancels out at the LNA. Whilst providing the necessary levels of CM isolation, one drawback of this architecture is the requirement for a Balun, as the additional loss from this component adds to the Rx insertion loss and receiver noise figure.

5 Limitations of electrical balance Duplexing

The ideal hybrid junction provides infinite isolation between conjugate ports when all ports are correctly terminated with matched impedances. However, in practice, the antenna impedance is not an ideal 50Ω resistor, but exhibits significant variation in the frequency domain, and has a significant reactive part. Furthermore, the antenna impedance may be perturbed by nearby objects, and can therefore also exhibit significant variation in the time domain [12]. Consequently, the balancing impedance must be adaptive in order to track temporal variation in the antenna impedance, requiring a system such as that depicted in Fig. 1.b, and the transmit to receive isolation will be limited by impedance mismatch between the antenna and balancing impedance.

To obtain isolation across a given bandwidth, the balancing impedance must equal the antenna impedance at all frequencies within that band. But, since the antenna impedance typically varies significantly with frequency, simple balancing networks cannot mimic the antenna impedance effectively over wider bandwidths. For example, the balancing impedance circuit can be adaptively tuned to maximize the transmit-to-receive isolation at the carrier frequency. This will provide extremely high (theoretically infinite) isolation at the carrier frequency, but at other frequencies in the transmit band, the antenna impedance and balancing impedance will not be perfectly matched, and the isolation at these frequencies will be therefore be reduced. This limitation in balancing is the dominant mechanism which limits the self-interference suppression achieved by EB duplexing, and since many antennas can exhibit relatively rapid variation in impedance with respect to frequency, this significantly reduces the *isolation bandwidth* of the EB duplexer. Furthermore, since the self-interference signal is spread across the transmit band, maximising the isolation at the carrier frequency is not necessarily useful if this results in poor isolation in other parts of the transmit band. Instead, the goal is to maximize the receiver SNR, which is achieved by minimizing the mean Tx-Rx gain taken across the whole Tx band [6]. This optimum balancing occurs when the balancing impedance is chosen to minimize the mean square error between the balancing reflection coefficient and the antenna reflection coefficient: *MMSE balancing*. It can be shown [6] that for simple balancing networks, such as the parallel RC circuits used in [11] and [10], that this *maximized isolation* is proportional to the variance of the antenna impedance with respect to frequency.

6 EB Duplexer performance

Prototype EB duplexers reported in [11] and [10] demonstrated high transmit to receive isolation over wide bandwidths where the antenna is modelled as a near ideal 50Ω resistance. Whilst these prototype duplexers have demonstrated that an EB duplexer can be successfully fabricated on-chip with reasonable Tx insertion loss and receiver noise figure, the omission of real antennas from these

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prototypes means that the observed isolation bandwidth may not be achievable in practice. Fig. 4 compares these results to simulations reported in [6] which incorporate a measured antenna reflection coefficient (and therefore model the real antenna perfectly), and to novel measurements from a discreet hardware prototype EB duplexer including antenna presented here.

6.1 Hardware EB Duplexer

Fig. 4.d depicts the hardware EB duplexer in the laboratory. The balancing impedance is implemented using an electromechanical impedance tuner, which provides extremely accurate balancing impedance control, but has a slow tuning speed. The balancing impedance and antenna are connected to a microstrip hybrid junction, and the lengths of the coaxial transmission lines for the antenna and balancing impedance were selected such that the group delay of the balancing and antenna reflection coefficients are approximately equal (thus minimizing the relative phase variation between the two reflection coefficients). The antenna used is the same antenna which was embedded into the circuit simulations in [6] (Fig. 4.c), this being a Taoglas PAD710 multiband cellular antenna. The transmit to receive isolation is measured using a Vector Network Analyser (VNA), and these measurements also inform a simple gradient descent minimisation algorithm running on a PC, which controls the balancing impedance in order to minimise the mean Tx-Rx gain across a 20MHz (using MMSE balancing [6]).

6.2 Performance Comparison

Circuit simulations reported in [10] model the antenna as a 50Ω resistor with some small parasitic capacitance and inductance, as depicted in Fig.4.a. The results show a *60dB isolation bandwidth* (the bandwidth over which at least 60dB of Tx-Rx isolation is achieved) of approximately 50MHz. Similar isolation bandwidths were achieved by the hardware prototype also reported in [10] which emulated the antenna on-chip using a similar circuit to the simulated antenna model. The transmit to receive isolation observed in this case has a higher peak isolation and a much larger isolation bandwidth as compared to the simulations which include a measured antenna and the hardware duplexer presented here. Simulations in [6] report 60dB isolation bandwidths of less than 10MHz, and the hardware duplexer did not achieve 60dB of isolation. This clearly demonstrates the significant detrimental impact of the frequency variant antenna impedance. The hardware duplexer shows comparable performance to that predicted by the simulation, although there is some additional reduction in transmit to receive isolation due to the increased frequency domain variation in the balancing impedance. Simulations recently presented in [13] use a more realistic printed inverted F antenna (PIFA) model (Fig.4.b); these simulation results are in much closer agreement with measured performance. Furthermore, the isolation achieved by the prototype EB duplexer exceeds that of small form factor antenna separation architectures (~30dB) and circulators (~15dB).

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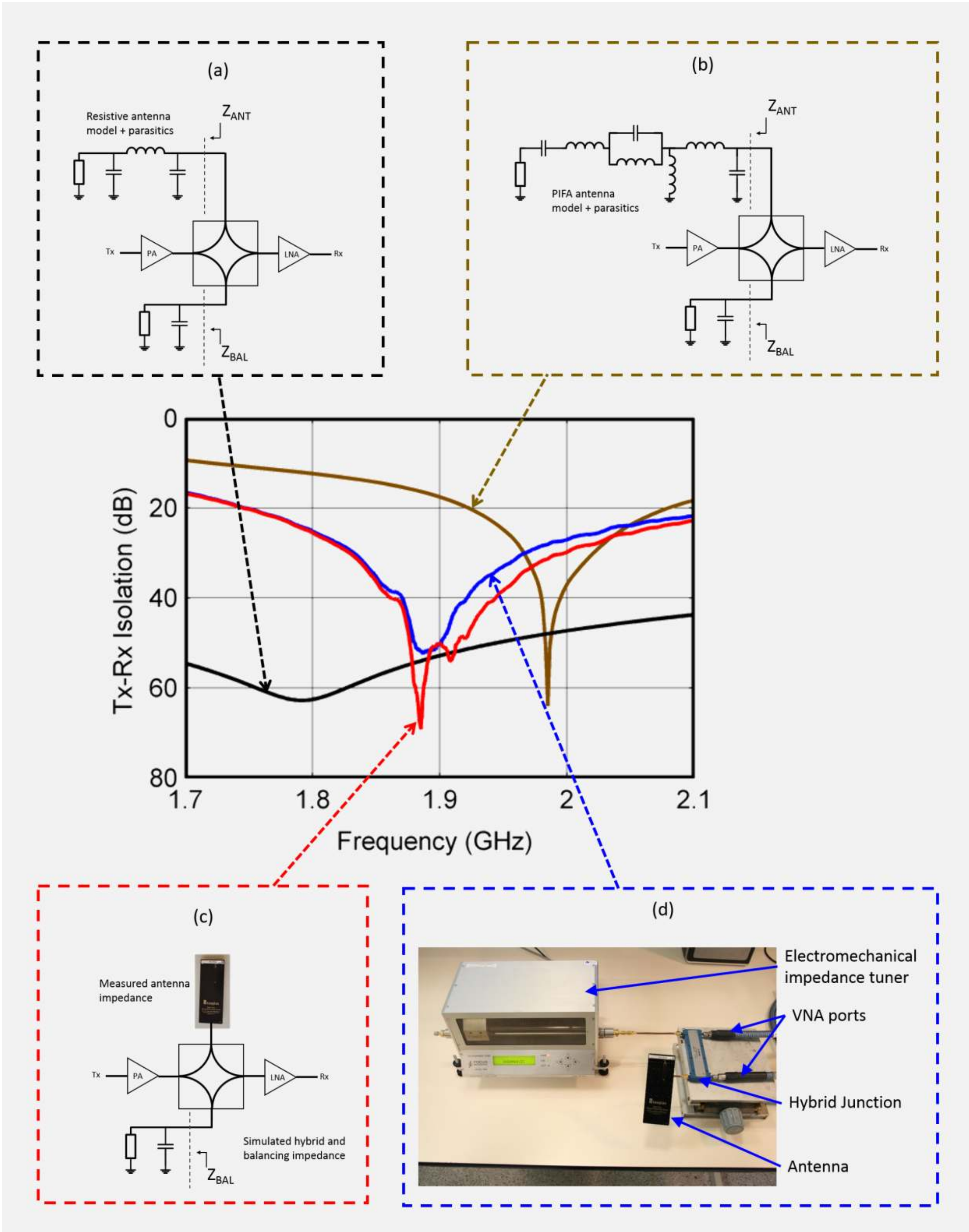

Figure 4: Comparison of reported results for duplexer isolation. a) Simulation with resistive antenna model [10]*, b) Simulation with lumped element PIFA antenna model* [13]*, c) Simulation with measured antenna data* [6]*, d) Measurement of hardware prototype EB duplexer.*

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7 Duplexer Adaptation

As shown, the matching between the antenna impedance and the balancing is the critical factor determining the transmit to receive isolation, and hence the suitability of this technology for use in Full-Duplex transceivers. Frequency domain variation in the antenna and balancing impedances has been shown to limit the transmit-to-receive isolation, however, the antenna impedance may also be time variant due to interaction with objects in the environment. EB duplexing, being a single antenna duplexing technique, is well suited to small form factor device applications, however it is well known that antennas in handheld devices can exhibit large variation in impedance due to interaction with the user [12]. To maintain Tx-Rx isolation the balancing impedance must track the antenna impedance as it changes, requiring the adaptive architecture depicted in Fig. 1.b. The performance of an EB duplexer is determined by the ability of the balancing impedance to mimic the antenna impedance in the *time domain and the frequency domain,* and therefore the design of the balancing network is critical to the resulting duplexer performance. Understanding the temporal properties of the antenna impedance, both in terms of the *range of variation*, and the *rate of change*, is therefore vital to be able to design an effective balancing network.

Adaptation range

Antenna impedances can vary over a relatively wide range due to environmental effects. Furthermore, full duplex radio is one facet of a general trend towards fully reconfigurable radios, capable of operation at a wide range of frequencies. Antenna impedances may typically exhibit vastly different impedances even at relatively closely spaced operating frequencies, making the range of possible impedances even larger when multiband operation is required. Antenna Tuning Units (ATUs) [14] provide dynamically controlled impedance matching for the antenna, improving efficiency, and have become common in handheld devices. Including an ATU in the EB transceiver would also have the important benefit of reducing the range of impedances presented to the duplexer, reducing range requirements for the balancing impedance, as depicted in Fig. 5.a.

Adaptation speed

In a practical system, any adaptive balancing impedance would be limited to some finite adaptation rate. As the antenna impedance fluctuates, the difference between the antenna impedance and balancing impedance will increase, thereby reducing the Tx-Rx isolation. The balancing impedance must track these changes at a rate which prevents this error from becoming unacceptably large. In this article, novel results demonstrating the impact of different tracking speeds for the balancing impedance are presented, and requirements for the balancing network adaptation performance are discussed.

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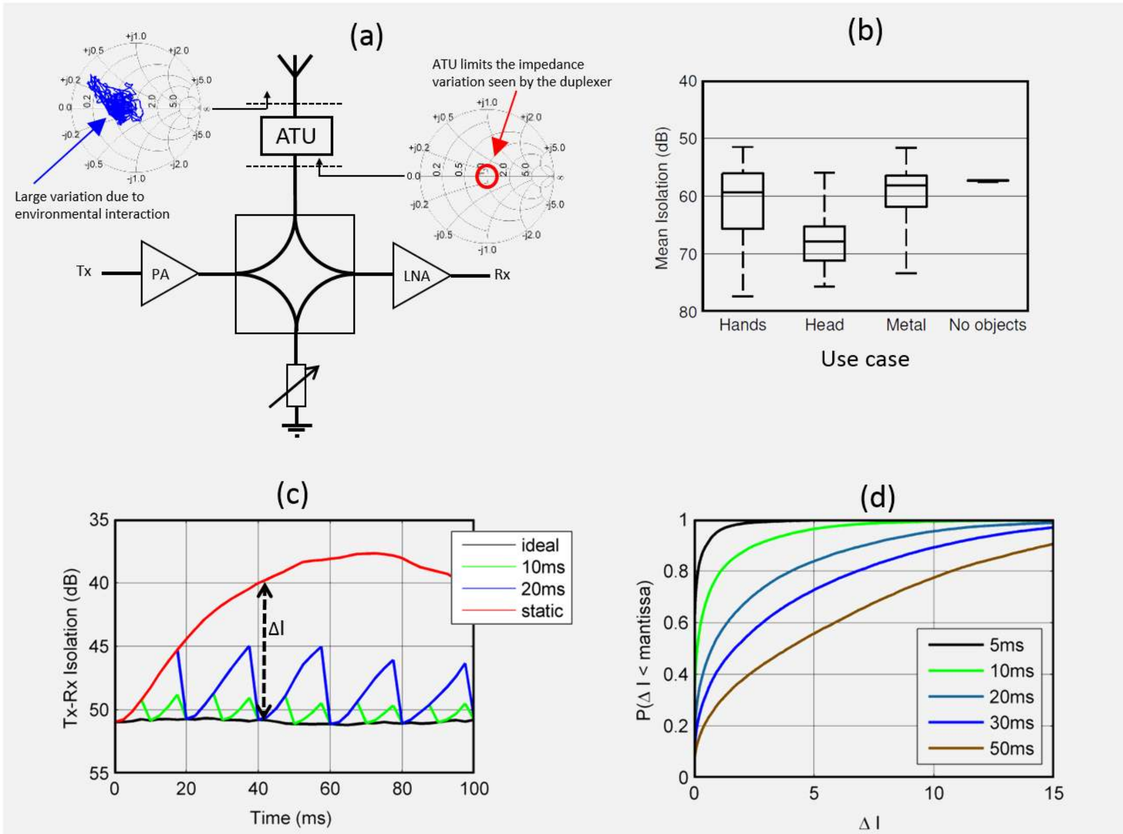

Figure 5: a) Antenna tuning unit (ATU) incorporated into electrical balance duplexer. b) Variation in maximized EB duplexer isolation due to user interaction at 1960MHz [15]*. c) Simulated time domain variation in Tx-Rx isolation for 4 types of adaptive balancing impedance. d) CDF curves for isolation degradation for 5 different balancing impedance update rates.*

As was the case in [6] and [15], circuit simulations with measured antenna data were used to investigate the Tx-Rx isolation of an EB duplexer (Fig. 4.c). The comparison between this simulation method and measured hardware duplexer presented in Fig. 4 demonstrates the validity of this technique. To observe the changes in antenna impedance typical for a handheld device with an interacting user, the antenna was placed in a plastic mobile phone housing, and multiple antenna reflection coefficient measurements were taken as a the "user" held the "device" and emulated browsing and texting movements. Reflection coefficient measurements were taken at 2.5ms intervals for a period of over 20s, and these measurements were then incorporated in to a circuit simulation which includes an adaptive balancing impedance with a variable adaptation rate. The measurements were performed over a 20MHz bandwidth centred at 1.9GHz, and the duplexer performance metric used is the mean Tx-Rx isolation across this band. Full details of the circuit simulation are given in [15], where the simulation was used to investigate the variation in Tx-Rx isolation in browsing and voice call scenarios, and with the device is placed on a metal surface, under the assumption that the adaptive balancing is ideal (i.e isolation is always maximized). Fig. 5.b shows results from [15], where the simulated mean Tx-Rx isolation values determined for each antenna measurement are grouped through their quartiles. These results show that provided that the balancing impedance is able to adapt, isolation of over 50dB was maintained. The simulations in [15] assumed ideal balancing

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adaptation, such that the duplexer isolation is limited only by frequency domain variation in the antenna and balancing impedances, whereas the simulation results presented here show the additional degradation in Tx-Rx isolation caused by updating the balancing impedance at a finite rate. Fig. 5.c shows the time domain variation in Tx-Rx isolation for four different simulated balancing networks. The ideal network tracks the antenna impedance perfectly. The "static" balancing network is tuned to maximise the duplexer isolation at t=0, and is then not updated. The degradation due to the untracked variation in the antenna impedance can be clearly seen. After 40ms the isolation drops to below 40dB, and was seen to go as low as 19dB (not shown on graph). The remaining two curves on Fig. 5.c show the Tx-Rx isolation when the balancing impedance is updated at 10ms, and 20ms. As would be expected, the higher update rate keeps the isolation closer to its maximized value. The additional degradation due to imperfect balancing impedance tracking, ΔI, is the difference in isolation as compared to the ideal balancing curve, and this metric is of interest when developing requirements for the impedance tracking.

7.1 Adaptation design considerations

As is the case with many types of system, the designer of an EB duplexer may seek to guarantee some level of isolation. To achieve this, the isolation budget of the system would need to include margins to account for any variation in the isolation (in much the same way that radio link budgets include fading margins). Consequently, understanding the variation in isolation is vital to the design of the system. Fig. 5.d depicts the cumulative distribution function (CDF) of the observed isolation degradation (ΔI) for a range of update rates, and provides useful information to the designer. For example, if only a 3dB degradation margin can be accepted, then for this system the update rate must be at least 5ms. However, given the variable nature of the isolation, it may be more appropriate to specify the performance statistically. For example, if the criteria is less than 3dB degradation for 90% of the time, then a 10ms update rate would be acceptable. It is also pertinent to note here that this rate of adaptation is relatively slow; adapting to user interaction is unlikely to be a problem for a practical EB duplexer.

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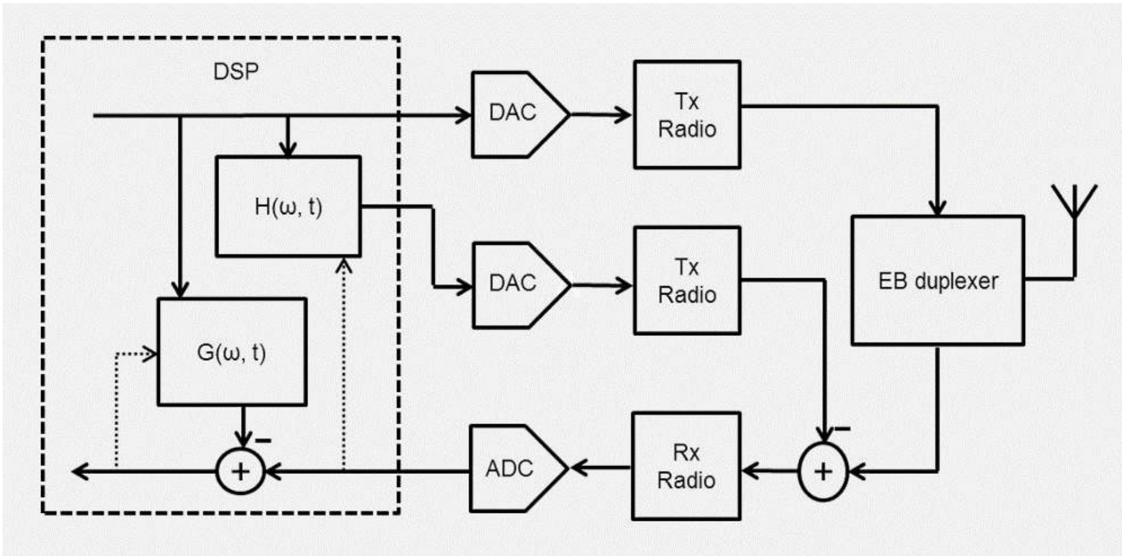

Figure 6. Possible architecture for a single antenna full duplex radio system incorporating electrical balance, active analog cancellation, and digital baseband cancellation [6].

8 Research opportunities

This newly rediscovered technology leaves various research opportunities remaining:

- **Combining EB with other self-interference suppression techniques.** Typically, full duplex radio systems combine various methods to achieve high levels of isolation. Full duplex architectures exploiting EB duplexing, such as that proposed in [6] and depicted in Fig. 6, which combines EB duplexing with analog and digital cancellation. Architectures such as this require much further investigation.

- **Antenna and balancing impedance co-design.** Since the impedance matching between these two components is critical to the isolation there is potential benefit to be had from designing the two such that their impedance vary in a similar fashion, and this could significantly widen the isolation bandwidth. Conversely, it may be case that the antenna type is not known to the designer of the duplexer (typical for Radio Frequency Integrated Circuits where a single IC design finds its way into a wide range of end products). In this case the duplexer should be designed to cope with an arbitrary antenna impedance.

- **EB duplexer adaptation in other environments.** The novel results presented in this article investigate the EB duplexer adaptation requirements in user interaction scenarios. Other dynamic environments will present different requirements (e.g. vehicular communication).

- **Balancing impedance implementation.** Deep submicron CMOS implementation is possible [10], however microelectromechanical (MEMS) tunable components may offer advantages in terms of linearity, power handling, and resolution. Recent publications [13] have also introduced balancing impedance designs which can match the antenna impedance at two frequency points, which is of clear benefit for FDD applications, but should also be investigated to determine the possible improvement in IBFD isolation bandwidth.

9 Conclusion

Electrical Balance duplexing offers high Tx-Rx isolation over wide bandwidths, but requires just one antenna and can be implemented on-chip, making this architecture well suited to small form factor devices. The transmit-to-receive isolation achievable using this technique is determined by how effectively the balancing impedance can mimic the antenna impedance, in both the time and frequency domain. Consequently, the isolation performance is limited by frequency domain variation in the antenna impedance, and the ability of the adaptive balancing impedance to track changes in the antenna impedance. Various contributions reporting simulated and measured duplexer isolation performance have been compared, and it has been shown that frequency domain variation in the antenna impedance is the primary factor determining transmit-to-receive isolation in practical duplexers. Circuit simulations incorporating measured antenna data have been used to investigate the effect of imperfect duplexer adaptation on the Tx-Rx isolation in user interaction scenarios. It was shown that a balancing impedance update rate of 10ms was adequate to ensure isolation degradation of less than 3dB for 90% of the time. EB duplexing offers significant further research opportunities and full duplex architectures exploiting electrical balance require further investigation.

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