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# Directional antenna-based single channel full duplex

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**Abstract:** Single-channel full-duplex (SCFD) radio has recently gained significant attention. It can not only double link throughput, but also provide the capability to solve a few challenging problems in half-duplex wireless systems, including hidden terminals, loss of throughput due to congestion, and large end-to-end delays. Recent works on SCFD have achieved full-duplex communication and claimed to have solved the aforementioned problems. However, when applied to a wireless network consisting of more than three nodes, they fail to solve these problems. One can conclude through analysis that, SCFD with omni-directional antenna as both transmit and receive antennas is inherently incapable of solving these problems. In this study, the authors propose a directional antenna-based solution of SCFD architecture, including a new SCFD radio prototype and a new medium access control (MAC) protocol [differential localization MAC (DL-MAC)] for wireless networks. Experiments on real nodes verify the authors' solution and their radio prototype achieves up to 93% link through put gain over half-duplex system. Numerical simulations show that the network capacity of their solution can be increased by nearly 200%, compared to a half-duplex system in a large-scale wire less network.

## 1 Introduction

Full duplex serves important functions in wireless communications. In full duplex, a node can transmit and receive signals simultaneously. It has been shown that full duplex can solve three important problems for existing wireless systems including hidden terminals, loss of throughput due to congestion, large end-to-end delays [1] and so on. However, in reality, full duplex is often achieved by using two separate channels in wireless communication. As a result, it defies the benefit of increasing link throughput with full duplex.

In recent times, there was a rejuvenated interest in single channel full duplex (SCFD) research [2, 3, 1, 4, 5]. SCFD aims to achieve full-duplex communication in a single channel. Compared to full duplex with two channels, it can double the link throughput, resulting in a higher spectrum efficiency in wireless interface. Recently, several prototypes [3, 1, 4] were proposed for SCFD. These solutions use omni-directional antenna for transmitting and receiving. It has been shown these solutions work well in a two-node communication environment. However, in a wireless network consisting more than three nodes, we can show that these solutions fail to provide a complete solution to address the aforementioned three problems in wireless network. Indeed, one can show that existing solutions with omni-directional antenna for both transmission and reception suffer from the fundamental limitation of co-channel interference. Detailed analysis will be presented in Section 2.

In this research, we propose a new SCFD radio architecture, which uses directional antenna for transmitting and omni-directional antenna for receiving. Our architecture is capable of doubling link throughput, compared to the full duplex with two separate channels, and solving the aforementioned three problems with half-duplex wireless communication. Our contributions in this study are multi-fold, including:

- We conclude via analysis that the single channel full duplex architecture based on using omni-directional antenna for both transmitting and receiving cannot provide a complete solution in a wireless network.
- We propose a complete SCFD radio architecture, called directional and omni-directional SCFD (DO-SCFD), which uses directional antenna for transmitting and omni-directional antenna for receiving, and implement a system prototype. Our architecture takes advantage of the front-to-back ratio of directional antenna, and combines two existing interference cancellation methods used in [1]. Experiment on real nodes shows that our prototype achieves up to 93% throughput increase compared to half-duplex system.
- We propose a medium access control (MAC) protocol based on our radio prototype, called differential-localisation MAC (DL-MAC) and simulate its operation in a testbed. Our numerical investigation suggests that our proposed MAC protocol entails a few salient features, including (i) supporting full-duplex communication in a wireless network, (ii) solving the three aforementioned problems in wireless network and (iii) greatly increasing network throughput compared to half-duplex and full duplex with two separate channels.

The rest of the paper is organised as follows. In Section 2, we analyse the limitations of the existing SCFD solutions. In Section 3, we present our proposed SCFD radio architecture and explain its working principle. In Section 4, we propose a new MAC protocol that works with our proposed radio architecture. In Section 5, we evaluate our proposed radio architecture with a system prototype and the MAC protocol with a simulation testbed. Related work is included in Section 6. Section 7 summarises this paper.

## 2 Motivational examples

In this section, we motivate our research through a case study of existing SCFD solutions. The cases we choose for discussion obey the following rules: (i) more than two nodes and one link are required. We will discuss the SCFD in the perspective of network consists multiple links, not in the perspective of isolated two nodes; (ii) the cases can work or be solved in a two-channel full-duplex system. SCFD should retain the full-duplex feature like two-channel full-duplex does; (iii) the cases should contain both data and controlling messages communicating; and (iv) two fundamental networking structures should be considered, including infrastructure-based network and *ad-hoc* network. Given that, we choose three typical cases are shown in Fig. 1, including hidden terminals, loss of throughput due to congestion and large end-to-end delays. All the three cases consist more than one link and can be solved in a two-channel full-duplex system. The hidden terminals case involves controlling messages communicating, the other two cases are about data communicating. The loss of throughput due to congestion case works in an infrastructure-based network, and the large end-to-end delay case works in an *ad-hoc* network. Therefore, the three cases are relatively comprehensive for us to study and discuss SCFD. We observe that the existing solutions, using omni-directional antenna for transmitting and receiving, are fundamentally limited not being able to solve the three cases with current half-duplex wireless systems. For convenience, we call the three aforementioned cases as basic problems in this paper. In this section, we motivate our research through a case study of existing SCFD solutions. We observe that the existing solutions, using omni-directional antenna for transmitting and receiving, are fundamentally limited not being able to solve the three problems with current half-duplex wireless systems. For convenience, we call the three aforementioned problems as basic problems in this paper.

Existing SCFD solutions [1, 5, 3, 4] use omni-directional antenna for transmitting and receiving. Although omni-directionality ensures network coverage, it sacrifices the ability which double channel full duplex owns, like solving the basic problems. The hidden terminals problem is shown in Fig. 1*a* including collision occurs at *B* when *A* and *C* both transmit to *B*. Hence *C* is out of *A*'s communication range, and it cannot sense *A*'s transmission. Actually, the hidden terminals problem has already been solved by request to send (RTS)/clear to send (CTS) mechanism, but due to the time cost of RTS/CTS handshakes, the throughput will slightly decrease. Full duplex is a natural way to solve the problem without loss of throughput: if *B* is a full-duplex node, without the RTS/CTS negotiation, it can tell *C* not to send any packet while it is receiving from *A*, therefore collision can be avoid. In this paper, we call the MAC protocol from [4] as MAC1 for convenience, it takes advantage of busytone to solve the problem. Once *A* sends to *B*, *B* will keep broadcasting a busytone unless it has data to send until *A*'s transmission finished. *C* will sense the busytone and refrain its transmission demand. It seems that the hidden terminals problem is solved. Actually, if we add a node *D* which is out of *B*'s communication range, and *D* wants to send packets to *C*. Hence *D* cannot sense the busytone, *C* will receive two signals, one is busytone, the other is from *D*. Collision occurs at *C*. If *B* sends data instead of busytone to *C*, then *C* will broadcast a busytone which will interfere *B*'s reception from *A*. So, MAC1 is not suitable to solve the hidden terminals problem in a network consisting more than three nodes.

The loss of throughput due to congestion case often occurs in WLAN, when there are multiple nodes planning to communicate between each other. Due to the structure of WLAN, a router node will be used for data forwarding, and it will become the bottleneck of WLAN communicating. The case is shown in Fig. 1*b* including *R* is an intermediate node which routes packets from $S_1$ to $D_1$ and packets from $S_2$ to $D_2$. When *R* is transmitting the packets received from $S_1$ to $D_1$, $S_2$ has to wait due to congestion. If *R* is a full-duplex node, *R* can transmit the received packets from $S_1$ to $D_1$ meanwhile receive packets from $S_2$, therefore congestion problem is mitigated.

In wireless sensor networks, sensors are organised in an *ad-hoc mode*, the data collected by a sensor would experience multiple hops of transmission to reach the final sink node. Therefore, the delay of data transmission could be large. As shown in Fig. 1*c*, the large end-to-end delays problem is that packets from *A* have to route via *B* and *C* to reach *D*. Due to half duplex, *B* must finish receiving a whole packet before it can send the packet to *C*. In full-duplex communication, once *B* decodes the destination address from the head of the packet which sent by *A*, it can initiate a transmission to *C* immediately. Therefore, there will be very small delays on intermediate nodes.

The two basic problems are solved using the same communication style of full duplex, which is every intermediate node sends while receiving. In this paper, we call this type of communication as continuous relay transmission. If every node is equipped with two omni-directional antennas, the continuous relay transmission will fail because *B*'s reception from *A* will be interfered by *C*'s transmission. The interference is inevitable due to the omni-directionality of both transmitting and receiving.

In the perspective of communication, omni-directional transmit and receive antennas will make estimation to be a bottleneck of achieving better SDFC communication. In the perspective of network, omni-directional transmit and receive antenna will cause co-channel interference which make SDFC fail to solve the basic problems. Now we conclude that SCFD with omni-directional antenna as both transmit and receive antennas is inherently incapable of solving the basic problems. This insight motivates us to design a complete SCFD solution, by using one directional antenna for transmitting.

## 3 DO-SCFD radio architecture

Motivated by our analysis in Section 2, we present our SCFD solution in the section, which uses directional antenna for transmitting and omni-directional antenna for receiving. Directional antenna has strong directionality which would significantly reduce self-interference and co-channel interference.

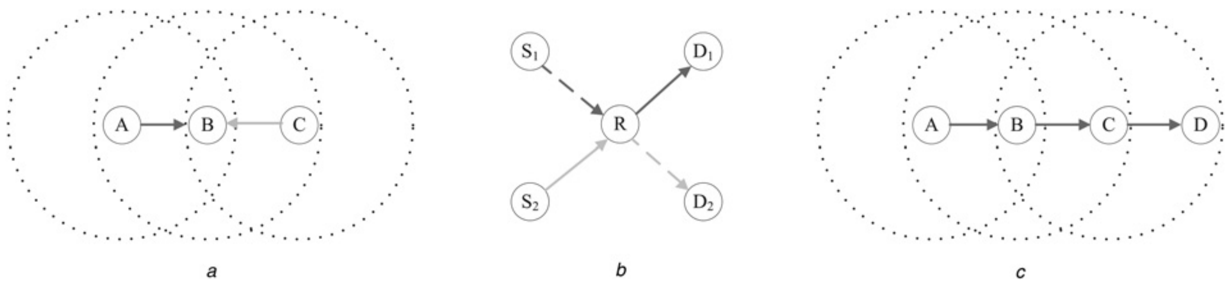


**Fig. 1** *Basic problems of wireless communication*

*a* Hidden terminals
*b* Loss of throughput due to congestion
*c* Large end-to-end delays


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### 3.1 Radio design

Self-interference is the main obstacle standing in the way of achieving SCFD. The more self-interfering power can be eliminated, the better an SCFD system can perform. Our SCFD radio has two antennas: the directional antenna is used as transmit antenna, and the omni-directional antenna is used as receive antenna, therefore we call the radio DO-SCFD radio (DO-SCFD Radio). The receive antenna is placed at the back of the transmit antenna. There is no distance restriction between two antennas, but according to [6], two antennas would affect each other when they are too closed, so as long as receive antenna and transmit antenna do not affect each other, they can be placed as closed as possible. To make sure the receive antenna is always behind the back of transmit antenna, when transmit antenna needs to point to a destination node, the transmit antenna is not rotated, instead, the radio device is rotated to point to the destination node.

Using directional antenna as transmit antenna is to make self-interfering signal directional, so that it will not interfere the receiver. Using Omni-directional antenna as receive antenna is to make sure the receiver can receive the intended signal no matter how the radio device rotate. Everett *et al.* [7] mentioned using directional antenna as both transmit and receive antennas where receiver uses a directional antenna, and it faces to the transmit antenna's back. The self-interference power at the receiver equals to transmitter's front-to-back (F/B) ratio adds antenna gains, then the self-interference power is not decreased as expected at the receiver. If the transmit antenna and the receive antenna are F/B, then the self-interference power at the receiver equals to transmitter's front power adds antenna gains, the self-interference power increased. So, directional transmit antenna and directional receive antenna cannot co-exist in SCFD radio. To the best of our knowledge, this paper is the first one that uses this antenna combination to achieve the SCFD.

As shown in Fig. 2, the radio design is similar to the one in [1], except that we take advantage of directional antenna's F/B ratio to cancel the self-interference power before it is received by the receive antenna. Combined with radio-frequency (RF) cancellation and digital cancellation methods, we can achieve at least 60 dB self-interference cancellation depends on the F/B ratio.

### 3.2 F/B ratio

An antenna is a passive device which does not offer any added power to the signal. Instead, an antenna simply redirects the energy it receives from the transmitter [8]. Omni-directional antenna redirects the energy uniformly in all directions; directional antenna redirects more energy in one direction and less energy in other directions. For directional antenna, main lobe is the direction which has more energy; side lobe and back lobe, therefore have less energy. F/B ratio is the ratio of power gain between main lobe and back lobe. If main lobe has a gain of 25 dB and back lobe has a gain of 5 dB, then F/B ratio is 20 dB. A common off the shelf-directional antenna has ~20–30 dB F/B ratio. To increase F/B ratio, there are two common ways: (i) as the antenna is a passive device which redirects the energy from the transmitter, if more energy is redirected to main lobe, then less energy will be in the back lobe, therefore F/B ratio increased and (ii) back lobe power mostly comes from wave diffraction. Less wave will diffract to the back through enlarging the reflector size of directional antenna, therefore F/B ratio increased. The authors [9, 10] analysed the back lobe of planar antenna, and they found that surface wave is another factor responsible for the back lobe. Through eliminating the surface wave, F/B ratio can be further improved to more than 10 dB. With the development of antenna technique, F/B ratio of directional antenna will keep increasing, and therefore the performance of DO-SCFD radio will keep improving.

### 3.3 RF interference cancellation and digital interference cancellation

RF interference cancellation cancels interference in the RF front end. A common RF canceller is Qh × 220 chip. The chip is used for cancelling a reference signal from an input signal, and it claimed to cancel up to 30 dB reference signal power. As shown in Fig. 2, the origin transmit signal is split into two branches: one is for transmitting via antenna; the other is for cancellation reference. Before the origin signal is sent to the reference port of the chip, it

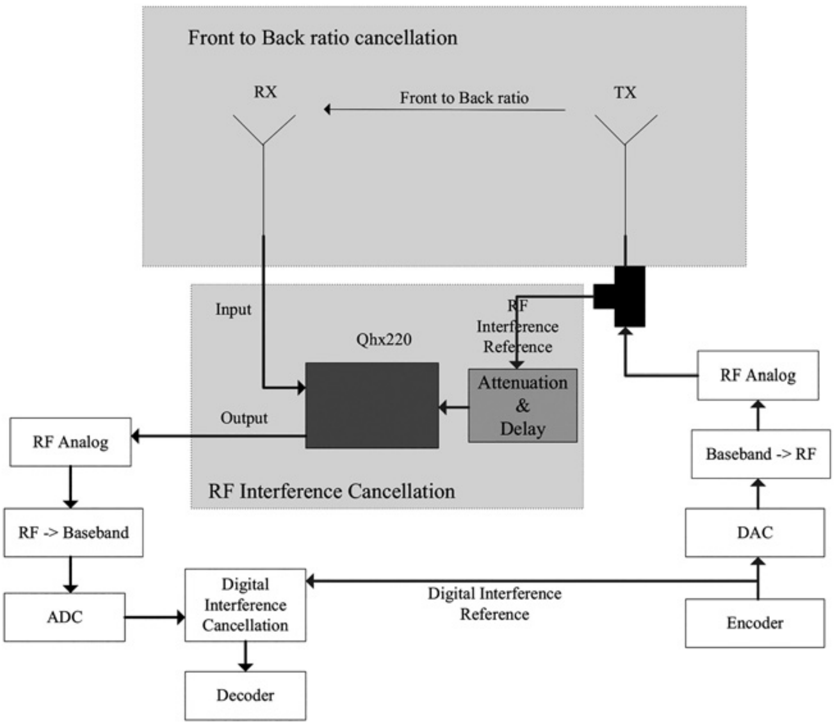


**Fig. 2** *SCFD radio design. It contains three parts: F/B ratio part takes advantage of the F/B ratio of directional antenna to cancel self-interference; RF interference cancellation part uses Qh × 220 chip to cancel self-interference in the RF front end; digital interference cancellation part cancels self-interference after ADC*

has to be delayed and attenuated according to the estimation. When the received signal is sent through the input port of the chip, the chip will output a clean signal with up to 30 dB power reduction of self-interference.

Digital interference cancellation cancels interference after analogue-to-digital converter (ADC). It uses the digital origin transmit signal to correlate with the digital received signal. If correlation occurs, the origin signal will be subtracted from the received signal. Digital interference cancellation is a good way to cancel interference, because it has a better estimation of phase shift. It can cancel ∼10–20 dB interference power. However, due to ADC saturation, if interfering signal power is much bigger than the others', after ADC, only interfering signal will be digitalised, and the other signals will be discarded. So, before entering the digital interference cancellation step, self-interfering power should be cancelled as much as possible.

A common off the shelf directional antenna has an F/B ratio of ∼20–30 dB, RF canceller can cancel ∼30 dB, and digital cancellation can cancel ∼10–20 dB. So, DO-SCFD radio can cancel ∼60–80 dB interference power.

## 4 DL-MAC protocol

In this section, we present a new MAC protocol for our proposed SCFD solution, working in a wireless network consisting more than three nodes. There are three goals in our MAC design: (i) to allow SCFD communication, (ii) to solve the basic problems and (iii) to increase network capacity. To accomplish all three goals, the MAC design takes advantage of an existing RTS/CTS mechanism DBTMA [11]. Based on the RTS/CTS negotiation, a novel MAC protocol called DL-MAC is proposed.

### 4.1 Design challenges

RTS/CTS negotiation is a practical way to solve the hidden terminals problem, although it will lose some throughput due to the negotiation process. As the RTS and CTS packets are very small, it will not affect the network performance. DL-MAC takes advantage of RTS/CTS negotiation in dealing with the hidden terminals problem, meanwhile it modified the RTS/CTS protocol to fit to our full-duplex prototype and to achieve the three goals.

In Figs. 5*b* and *c*, *B* is not in the transmission range of *C*, therefore *C*'s transmission will not interfere *B*'s reception. To increase network capacity, *C*'s transmission should be allowed. The problem is how does *C* know whether it will interfere *B*'s reception. If every node in the network is equipped with a localisation equipment like GPS, a node can realise its location and inform the location to its neighbours. With the knowledge of neighbours' locations, *C* can compute a topology and judge whether *B* is in the transmission range. This method requires an extra equipment which is expensive and not commonly equipped in today's communication nodes. Therefore, how to realise the relationship between *B* and *C* without the help of any extra equipment is a real challenge.

Both directional antenna and omni-directional antenna are used in our full-duplex radio, and we can take advantage of the antenna diversity. Directional antenna usually has a higher gain than omni-directional antenna. When directional antenna faces to a signal, the signal strength received by directional antenna will be higher than the signal strength received by omni-directional antenna. When directional antenna receives a signal using its back lobe, because of F/B ratio of directional antenna, the signal strength received by directional antenna will be much lower than the signal strength received by omni-directional antenna. We proposed an equation to describe the mentioned relationship between *B* and *C* based on the observation. The relationship is called transmitter to receiver (T2R). Fig. 3 shows the three relationships of T2R: receiver *B* broadcasts a signal. If *C* is face to *B* as shown in Fig. 3*a*, the signal will be received by the main lobe of *C*'s transmit antenna; If *C* is back to *B* as shown in Fig. 3*c*, the signal will be received by the back lobe of *C*'s transmit antenna; If *C* is side to *B* as shown in Fig. 3*c*, the signal will be received by the side lobe of *C*'s transmit antenna.

Equation (1) describes how to calculate T2R relationship, given by

$$\text{T2R} = \begin{cases} \textbf{face to} & : \; P_t - P_r \geq (1-k)(G_t - G_r - m), \\ \textbf{back to} & : \; P_t - P_r \in [T_l, T_u], \\ \textbf{side to} & : \; \text{otherwise}, \end{cases} \tag{1}$$

where $T_l = (1+k)(G_t - G_r - R_{F/B})$ and $T_u = (1-k)(G_t - G_r - R_{F/B})$. Suppose the signal strength transmit antenna received is $P_t$, the signal strength receive antenna received is $P_r$, gain of transmit antenna is $G_t$, gain of receive antenna is $G_r$, F/B ratio is $R_{F/B}$. Hence directional antenna has a beamwidth and signal strength measurement may have some errors, coefficients $k$ and $m$ are used for adjustment. $m$ refers to the region around the direction of maximum radiation of directional antenna, and it is expressed in decibels (usually $m$ equals to 3 dB; to avoid co-channel interference, $m$ can be increased). $k$ refers to the measurement error, and it is less than one. Hence we use the differential signal strength of transmit and receive antennas to judge the direction of transmitter, the MAC protocol is then called differential-localisation MAC.

### 4.2 Protocol description

How to adjust directional transmit antenna to point to an intended receiver automatically remains a problem in the MAC design. In this research, the full-duplex prototype is implemented in a static wireless network, and each transmit antenna has already pointed to the intended receiver. Transmit antenna is set to have same transmission distance as receive antenna, which can be achieved by tuning down the transmitting power of transmit antenna. As transmit antenna and receive antenna are closed to each other, therefore the distance between them is ignored in our MAC design (Fig. 4).

*4.2.1 Transmitter:* When a transmitter needs to send data, it has to ensure the transmission will not interfere any existing receiving node. It is well-known that, RTS–CTS negotiation will enable a transmission when the transmitter receives the CTS reply from the receiver. Therefore, before an SCFD transmission, the transmitter should check its message queue to ensure there is no valid CTS. If there are one or more CTS packets, it means there are one or more receivers in its transmission range receiving data, and its

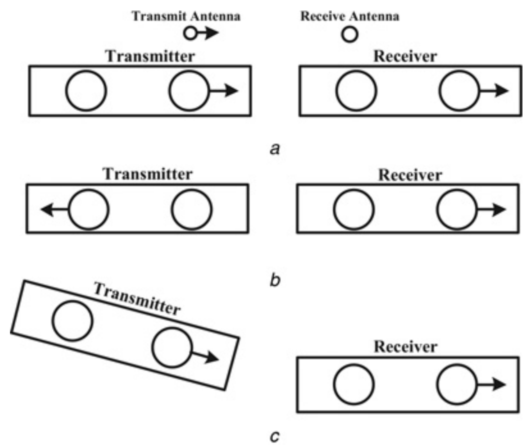


**Fig. 3** *T2R relationships*

*a* Transmitter *faceto* receiver. Receiver can rotate as long as its receive antenna is faced to the transmitter
T2R relationship is *faceto*
*b* Transmitter *backto* receiver. Transmitter faced to the opposite direction of receiver
T2R relationship is *backto*
*c* One situation of transmitter *sideto* receiver
All the T2R relationships which are not *faceto* or *backto* are *sideto*

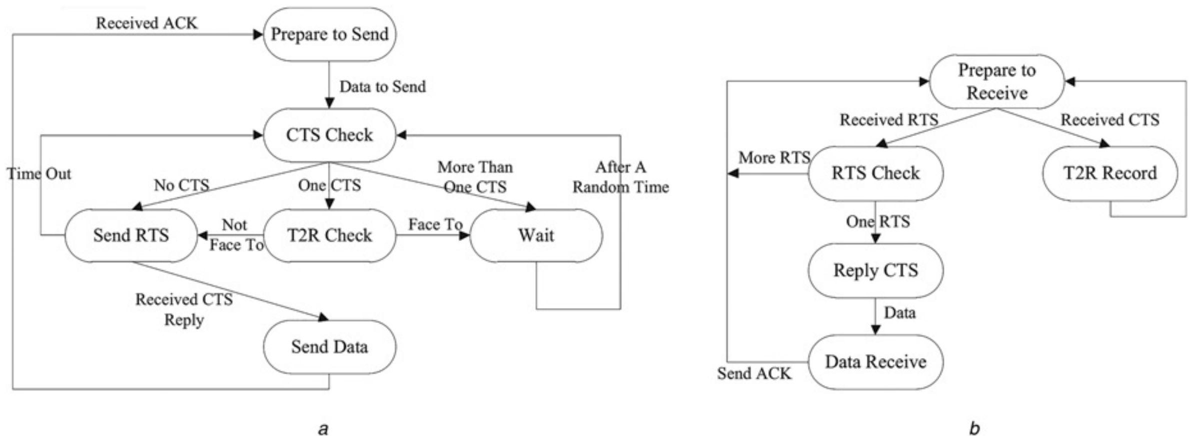


**Fig. 4** *DL-MAC algorithm*

*a* Transmitter
*b* Receiver

transmission has possibility to interfere the receiving node. Moreover, based on our directional antenna SCFD prototype, a transmitter may not interfere a surrounding receiving as long as the un-intended receiver is not in the range of the main lobe of the transmitter. In other words, as shown in Fig. 3, if the transmitter is not face to the un-intended receiver, the existing receiving will not be interfered. According to (1), a transmitter can aware its orientation to a receiver, therefore if there is only one CTS and the transmitter is not face to the receiving receiver, it can send an RTS to its intended receiver for later data transmission. However, if there are more than one CTS, it would be difficult for us to determine the potential interference to other receiving receivers, therefore the transmitter has to wait a random time and go through the whole procedure.

*4.2.2 Receiver:* If a receiver receives more than one RTS, it means there are two or more transmitters around, a CTS reply may cause potential collision. Therefore, it will not reply CTS until only one valid RTS exists.

### 4.3 Typical use cases

In this subsection, we present five typical use cases of DL-MAC in real network, as illustrated in Fig. 5.

Example 5a shows a basic full duplex communication. *A* has not received any CTS packets, so *A* sends an RTS packet to *B*; *B* has received only one RTS packets, so *B* broadcasts a CTS reply to *A*. Link *AB* is established. When *B* wants to send packets to *A*, *B* has not received any CTS packets, it sends an RTS packet to *A*; *A* has received only one RTS packets, so *A* broadcast a CTS packet to *B*, then link *BA* is established.

Example 5b shows a typical half-duplex communication using directional antenna. Link *AB* is already established, when *C* wants to send packets to *D*, *C* checks that it has received a CTS packet from *B*. *C* gets the T2R relationship from RTS/CTS history table. The relationship is side to, therefore *C* sends an RTS packet to *D*. *D* has not received any RTS packets because RTS packets are sent by directional transmit antenna, and *D* is not in the transmission range of *A*. Therefore, *D* broadcasts a CTS packet to *C*, and link *CD* is established.

Example 5c shows a continuous relay transmission, which all nodes are in *A*'s communication range. After link *AB* is established, when *B* wants to send packets to *C*, it checks that it has not received any CTS packets, then it sends an RTS packet to *C*; *C* has received only one RTS packet, so it broadcasts a CTS packet to *B*. Link *BC* is established; when *C* wants to send packets to *D*, *C* finds that it has received a CTS packet from *B*. *C* checks the T2R relationship and finds that the T2R is side to, so it sends an RTS packet to *D*; *D* has received only one RTS packets, so it broadcasts a CTS packet back to *C*. Then link *CD* is established. Compared to half duplex using omni-directional antenna only allows one link to communicate in this example, DL-MAC achieves three.

Example 5d shows a situation that co-channel interference occurs. Let us see how DL-MAC avoids this situation. After link *AB* is established, when *B* wants to send packets to *C*, and it has not received any CTS packets, so *B* sends an RTS packet to *C*. *C* has received two RTS packets, which are from *A* and *B*, so, it will not reply a CTS packet, and link *BC* is failed to be established.

Example 5e is a continuous relay transmission, which can solve loss of throughput due to congestion, and large end-to-end delays problems. After link *AB* is established, when *B* wants to send to *C*, *B* checks and finds that it has not received any CTS packets; *B*

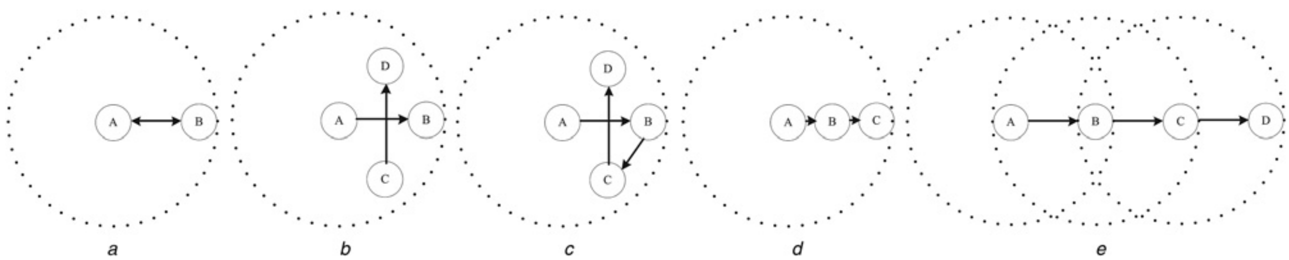


**Fig. 5** *Some examples of how DL-MAC works*

*a* Basic full-duplex communication
*b* Typical directional communication which two links are not interfering each other
*c* Full-duplex communication which includes four nodes in the same communication range of *A*
*d* Case which communication is not allowed
*e* Continuous relay transmission

sends an RTS packet to $C$; $C$ has received only one RTS packet, so, it broadcasts a CTS packet back to $B$, then link $BC$ is established; when $C$ wants to send to $D$, $C$ checks and finds that it has received a CTS packet from $B$. $C$ checks RTS/CTS history table and finds that the T2R is back to, then $C$ sends an RTS packet to $D$; $D$ has received only one RTS packet, so $D$ replies a CTS packets to $C$, and link $CD$ is established.

There are more co-existing links in Examples 5c and 5e, which greatly increased network capacity compared to half-duplex system; Examples 5a, 5c and 5e show the full-duplex communications; Example 5e shows a continuous relay transmission, which can solve the loss of throughput due to congestion and large end-to-end delays problems and the hidden terminals problem is solved by an RTS/CTS mechanism. Therefore, the three goals are all achieved.

## 5 Performance evaluation

In this section, we present the performance evaluation for our proposed SCFD solution. Specifically, we build a system prototype from Universal Software Radio Peripheral (USRP). Two USRP nodes are used to test a point-to-point SCFD communication; four USRP nodes are used to verify the aforementioned five examples. In addition, simulation is also used to test the performance of DL-MAC in a large-scale wireless network.

### 5.1 Prototype performance verification

The experiment setup in this research is similar to [1]. Two 2.4 GHz ISM radio RFX2400 daughterboards are used on each USRP node. Both transmit antenna and receive antenna are plugged in transceiver port on different daughterboards. Patch antenna which has 30 dB F/B ratio is used as transmit antenna. A Zigbee PHY for USRP radios from UCLA is used as a modulation/demodulation scheme. The experiment uses a band with a centre frequency of 2.48 GHz.

One USRP node is used to test how much self-interference our full-duplex prototype can cancel. As shown in Fig. 6, if transmit antenna is faced to receive antenna, the received signal strength is ∼–10 dBm; if receive antenna is placed behind the back of transmit antenna, the signal strength is ∼–40dBm, about 30 dB self-interference is cancelled. When RF interference cancellation and digital interference cancellation methods are added, the signal strength is ∼ –70 dBm, another 30 dB self-interference is cancelled. We did not achieve a 40 dB cancellation as [1] mentioned using RF interference cancellation and digital interference cancellation, and the reason probably is our inaccurate estimation in RF interference cancellation step, which proves that estimation is a bottleneck which will restrict the implementation of SCFD.

To compare the throughput between full duplex and half duplex, as shown in Fig. 7*b*, two USRP nodes are used. Node 1 is fixed to a place, and node 2 is moved to ll different places of the second floor of campus main building. As shown in Fig. 7*a*, full duplex can almost double link throughput compared to half duplex. Up to 93% higher throughput is achieved by full duplex than half duplex. However, when link quality is not good, full duplex will perform even worse than half duplex. The reason probably is the signal multi-path reflection. The self-interfering signals reflected back will severely affect full-duplex reception when link quality is not good. Therefore, to eliminate multi-path effect in full-duplex communications will be our future work.

Four USRP nodes with four 30° beamwidth directional antennas are used to verify the five examples in Fig. 5. Experiments show the same results as suggested in Fig. 5. Actually, four USRP nodes are far from enough to test MAC performance in a large-scale network. Therefore, simulation tools are used.

### 5.2 Large-scale simulations

In the simulation, the distance between transmit antenna and receive antenna is ignored because it is relatively much smaller than the distance between two nodes. A wireless network is setup in a 500m × 500m area; the number of wireless nodes is varied from 50 to 1000; the communication radius is set to 100 m. A pre-generated transmission table is used before every simulation. The transmission table randomly chooses a destination node for each node from its neighbour nodes. Using the same transmission table, simulations will test how many links can co-exist in the network using different MAC protocols. Three MAC protocols are used in simulation: DL-MAC protocol, RTS/CTS protocol of half duplex [11] and MAC1 protocol.

In this simulation, we use the number of co-exist links as a metric to measure the network capacity [12]. As shown in Fig. 8*a*, when there are 100 nodes in the network and beamwidth of directional antenna is 15°, there are averagely 33 co-exist links. Several continuous relay transmissions of more than four nodes in this figure prove that DL-MAC can solve the basic problems. As shown in Fig. 8*b*, the RTS/CTS protocol of half duplex achieved averagely 12 co-exist links which is much less than DL-MAC. Fig. 8*c* is an SCFD case using the MAC1. It achieved only 5 co-exist links and 19 invalid links because of severe co-channel interference. As shown in Fig. 8*d*, with the number of wireless nodes increased from 50 to 1000, the number of co-exist links will be steady gradually in all three cases. DL-MAC achieves ∼35 co-exist links and the RTS/CTS protocol of half duplex achieves ∼13 co-exist links, the MAC1 finally decreases to no co-exist links. DL-MAC shows greatly network capacity increase compared to the other two MAC protocols. Fig. 8*e* shows how beamwidth of directional antenna will affect our SCFD performance. With

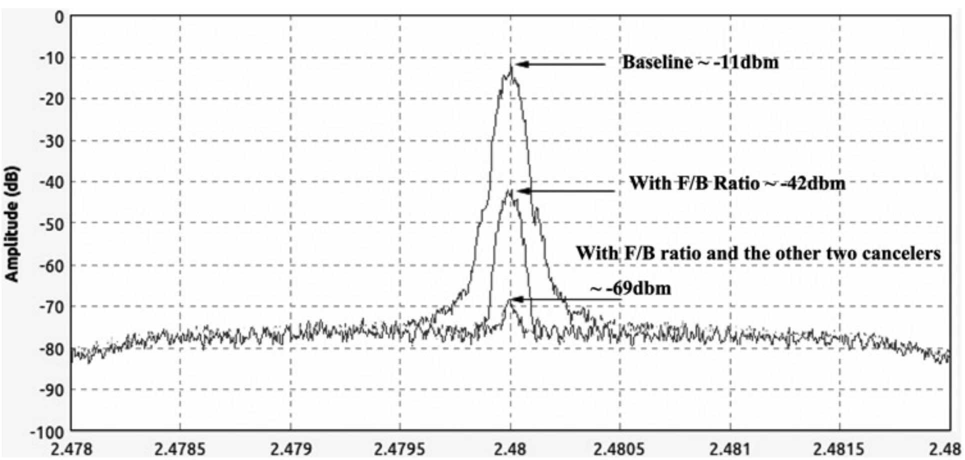


**Fig. 6** *Self-interference cancellation*


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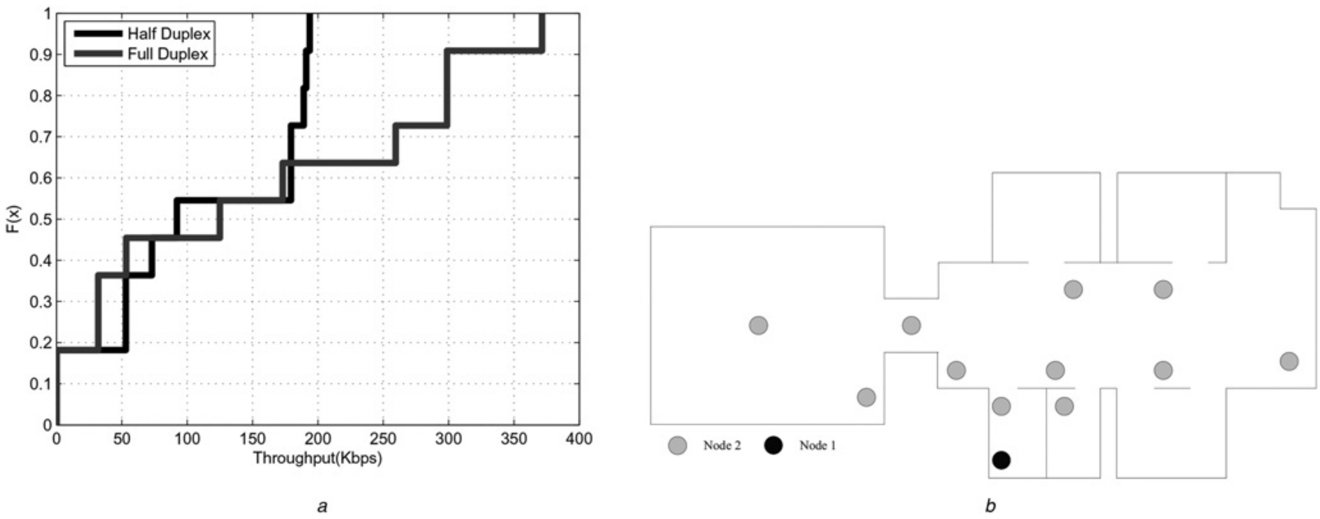


**Fig. 7** *Throughput experiments using two USRP nodes*

*a* Throughput
*b* Map

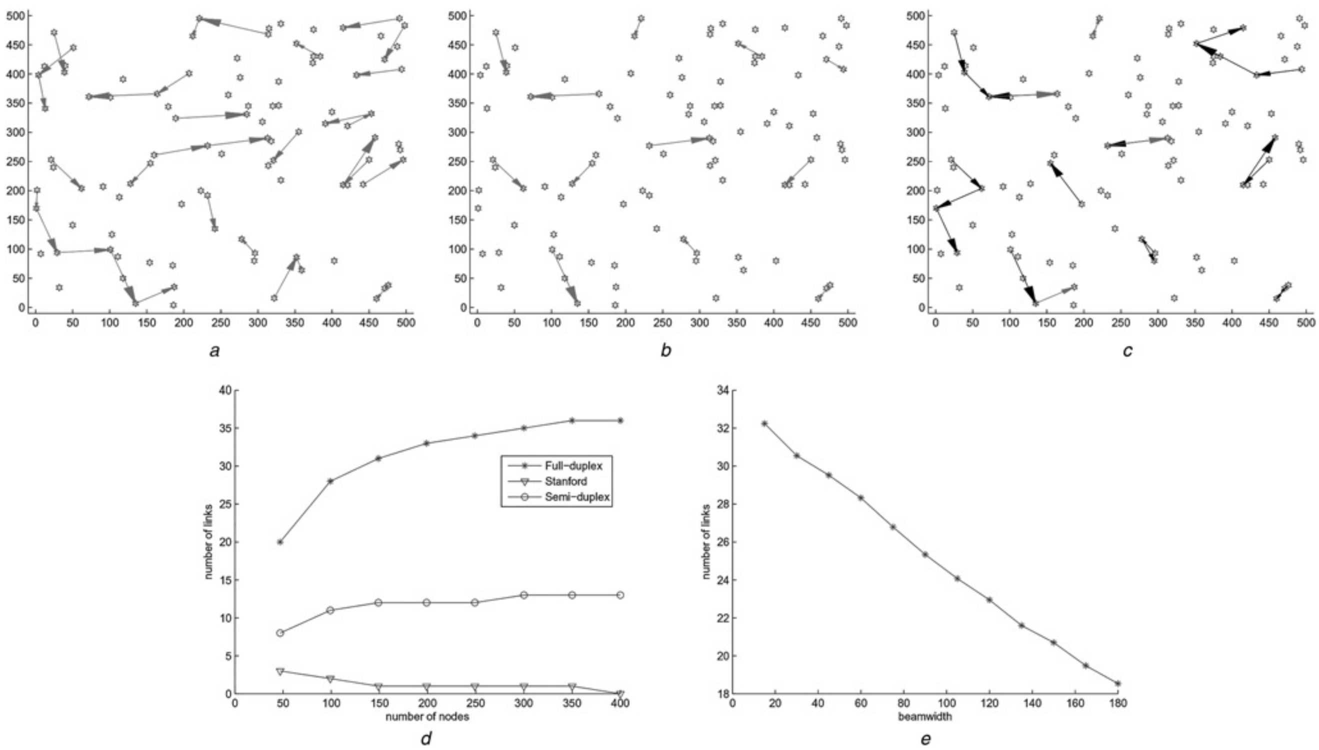


**Fig. 8** *Simulation results. (a)–(c) are co-exist links in a network of 100 nodes. The red line represents valid links, black lines represents invalid links (d) compares the number of co-exist links of three cases in a network with growing number of nodes from 50 to 400 (the Stanford is a protocol from [4]). (e) shows the effect of beamwidth changing to the number of co-exist links*

*a* DL-MAC on our SCFD system
*b* Half-duplex RTS/CTS mechanism
*c* MAC1 on an SCFD system using omni-directional transmit and receive antennas
*d* Links comparison
*e* Different beamwidth versus links

beamwidth increasing, the number of co-exist links is decreasing almost linearly. To achieve a better performance, directional antenna with small beamwidth is suggested.

The simulations show inspiring results. DL-MAC achieve ∼200% better performance than half duplex, and the results of MAC1 show the inherent incapability of omni-directional antenna as both transmit and receive antennas in achieving SCFD in a wireless network of more than three nodes.

## 6 Related works

SCFD is a hot topic in wireless communication. Before [5, 1, 4] studied the SCFD communication, some patents like Weissman and Yonah [13] proposed some full-duplex transceiver circuits design which dealt with received signals, therefore antenna was not being considered. A recent work Aryafar *et al.* [14] explored combining MIMO and full duplex to achieve both merits. However, it used a full-duplex radio prototype from [1] which will has the aforementioned limits in solving the basic problems.

Physical layer only concerns point-to-point communication, MAC layer will expand the communication to a network. Although there is only one paper [4] discussed about the full-duplex MAC, there are several papers discussed the MAC design of *ad-hoc* network using directional antenna. The authors [15, 16] gave a full solution of MAC design using an array of directional antennas which will bring extra cost. Choudhury and Vaidya [17] concerned a deafness problem in carrier sensing using directional antenna. The deafness problem is solved by using omni-directional antenna as receive antenna in our research. The authors [18, 19] discussed using directional antenna to increase network capacity and spatial reuse; it is a good effort to take advantage of directional antenna, and they also designed MAC protocols to achieve the purpose.

## 7 Summary and future work

In this paper, we proposed a directional antenna-based solution of SCFD radio for wireless network consisting of more than three nodes. The solution achieves three goals: (i) SCFD communication; (ii) solve the basic problems; and (iii) network capacity increase. Compared to half duplex and existing SCFD prototypes, our solution achieves a much better performance. Though the results are inspiring, there are still some problems must be solved in future works. Multi-path effect will strongly affect SCFD communication when link quality is low, therefore it must be solved. DL-MAC is incapable of dealing with multi-CTS cases which is that when a node received more than one CTS packet, how to judge whether the node should transmit an RTS packet is a real challenge.

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