Full Wave Simulation of the Transfer Response of the TX and RX Antennas in the Full-Duplex Wireless Communication Systems

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***Abstract*-In this paper, the full wave EM investigation on the self-interference channel characteristic of the full duplex wireless communication systems is presented. The FDTD method is used to obtain the channel response with different antenna configurations. The simulated results agree well with the measurement.**

I. INTRODUCTION

The spectrum resource is very important for modern wireless communication systems. The full duplex technique can double the spectrum efficiency by using the same frequency for both the transmitting and receiving simultaneously. The full duplex technique is very attractive, and may become a focus in the wireless communication field.

The largest challenge of a full-duplex system is to reduce the self-interference sufficiently [1], because the self-interference can be millions to billions of times stronger (60dB-90dB) than a received signal.

Well known digital and analog techniques, even combined them together [1], are not able to cancel self-interference sufficiently for full duplex. Motivated by these limitations, recent work has explored antenna placement as an additional cancelation technique. Antenna Separation is the simplest passive self-interference cancellation mechanism and it consists in loss in interference power due to propagation losses caused by separating the transmitting and receiving antennas at a node [6]. However, the reduction of the interference obtained with the antenna separation is limited especially for the mobile terminals.

To further cancel self-interference, J. I. Choi et al. propose a new technique, called antenna cancelation [1]. The system consists of two transmit antennas and a receive antenna. The distances between one TX and the RX is $\lambda/2$ longer than another. Although promising, antenna cancellation-based designs have some limitations. One of the limitations is the bandwidth constraint, a theoretical limit which prevents supporting wideband signals, which is crucial for a communication system.

It is found that the reduction of the self-interference is mainly limited by the transmitting response between the TX antennas and the RX antennas. Although the response can be measured, it is inconvenient during the tuning and optimization. On the other hand, the computation EM method can calculated the response steadily, especially for the optimization. Therefore, the FDTD method is used to simulate the channel characteristic of several cases.

In order to solve open spaces efficiently, absorbing boundary conditions (ABC) must be employed to truncate the computation domain. The first-order Mur ABC is a good choice, but the reflected wave is still larger than wanted. The second-order Mur ABC is often divergent. A new second-order absorbing boundary condition was used to FDTD method and the effect is similar to second-order Mur ABC.

II. MODEL FOR SELF-INTERFERENCE CANCELATION

A simple model is shown in Figure 1, where two nodes communicate with each other in the full-duplex mode. Each node has two antennas, one antenna is used for transmission and the other antenna is used for reception. $e_a(t)$ is the signal transmitted from Node a, $r_a(t)$ is the signal received at Node a, $h_{aa}(t)$ is the wireless channel from TX to RX of Node a, $e_b(t)$ is the signal transmitted from Node b, and $h_{ba}(t)$ is the wireless channel from Node b to Node a. Therefore, the received signal of the Node a is

$$r_a(t) = e_a(t) * h_{aa}(t) + e_b(t) * h_{ba}(t) \quad (1)$$

Where "$*$" is the convolution operator. If only Node a is used then the received signal at Rx of Node a is equal to $e_a(t) * h_{aa}(t)$. The estimate of $h_{aa}(t)$ is very useful to cancel the self-interference. Full Wave Simulation of the Transfer Response of the TX and RX Antennas in the full-duplex system can be used to get $h_{aa}(t)$.

As the communication from TX and RX is achieved through electromagnetic waves and such a macroscopic phenomenon is governed by Maxwell's equations. So the electromagnetic simulation can be used to find the self-interference channel $h_{aa}(t)$ and/or $H_{aa}(j\omega)$.

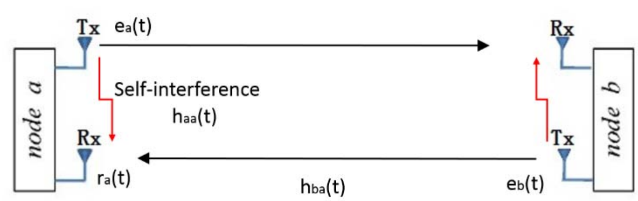

Figure 1. A simple model of full-duplex system

III. Analysis of Numerical Experiments

The FDTD method [10] is a very powerful tool to simulate the EM problems in both the time domain and the frequency domain. It is very suitable for the channel simulation of the full duplex systems.

A. Traditional explicit FDTD method

The iterative formula of explicit FDTD method are

$$\boldsymbol{E}^{n+1} = \frac{\frac{1}{\Delta t}-\frac{\sigma}{2\varepsilon}}{\frac{1}{\Delta t}+\frac{\sigma}{2\varepsilon}}\boldsymbol{E}^{n} + \frac{\frac{1}{\varepsilon}}{\frac{1}{\Delta t}+\frac{\sigma}{2\varepsilon}}(\boldsymbol{P}-\boldsymbol{Q})\,\boldsymbol{H}^{n+\frac{1}{2}} \quad (2)$$

$$\boldsymbol{H}^{n+\frac{1}{2}} = \boldsymbol{H}^{n-\frac{1}{2}} + \frac{\Delta t}{\mu}(\boldsymbol{P}-\boldsymbol{Q})\,\boldsymbol{E}^{n} \quad (3)$$

Where $\boldsymbol{P}$ and $\boldsymbol{Q}$ are discrete differential operator matrixes, and δ_x, δ_y and δ_z are central difference operators:

$$\boldsymbol{P} = \begin{bmatrix} 0 & 0 & \delta_y \\ \delta_z & 0 & 0 \\ 0 & \delta_x & 0 \end{bmatrix} \quad (4)$$

$$\boldsymbol{Q} = \begin{bmatrix} 0 & \delta_z & 0 \\ 0 & 0 & \delta_x \\ \delta_y & 0 & 0 \end{bmatrix} \quad (5)$$

$$\delta_x f_{i,j,k} = \frac{f_{i+\frac{1}{2},j,k} - f_{i-\frac{1}{2},j,k}}{\Delta x} \quad (6)$$

$$\delta_y f_{i,j,k} = \frac{f_{i,j+\frac{1}{2},k} - f_{i,j-\frac{1}{2},k}}{\Delta y} \quad (7)$$

$$\delta_z f_{i,j,k} = \frac{f_{i,j,k+\frac{1}{2}} - f_{i,j,k-\frac{1}{2}}}{\Delta z} \quad (8)$$

And the iterative formula are used on Yee cell.

A new absorbing boundary condition was used to this traditional FDTD method and the effect is similar to second-order Mur ABC.

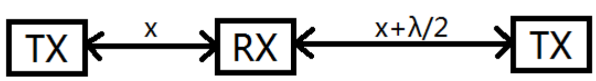

Figure 2. A scheme of antenna cancellation

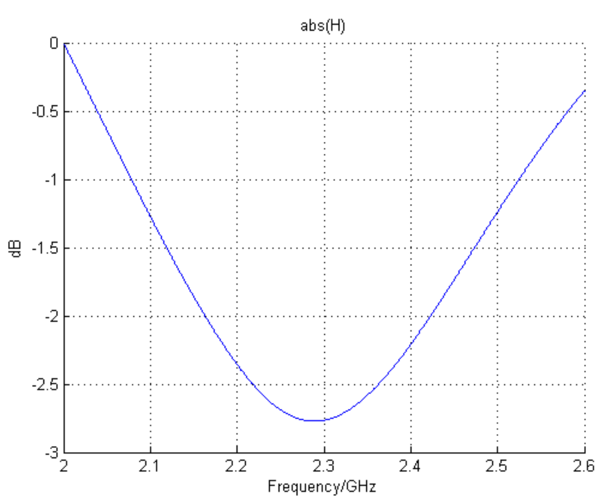

Figure 3. The channel of Scheme 1

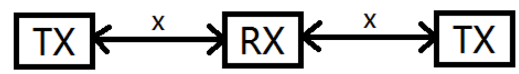

Figure 4. Another scheme of antenna cancellation

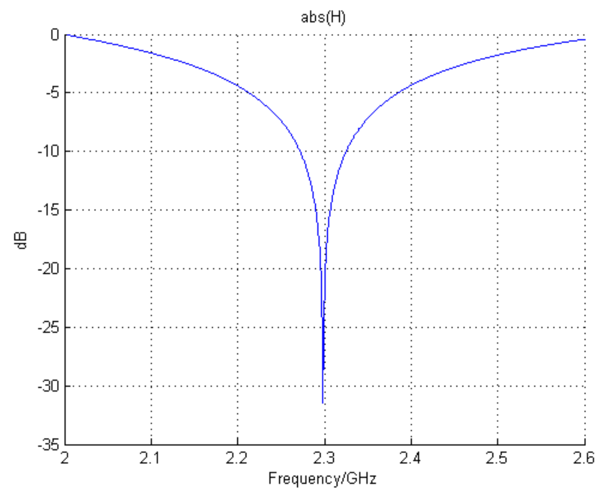

Figure 5. Channel without antenna cancellation

B. Antenna cancellation simulation

Antenna cancelation consists of two transmit antennas and a receive antenna. There are two schemes to achieve cancellation and one of them are shown in Figure 2. The left and right antennas are used to transmit signals, whereas the middle one to receive signals. The distances between one TX and the RX is $\lambda/2$ longer than another. So the two signal send by transmit antennas will arrive at the receive antenna with a phase difference of π which just implements a cancellation.

Using traditional explicit FDTD method, an ordinary case is calculated. All the antennas are placed in the central of the calculation space. The left antenna is 150mm away from the central antenna, whereas the right antenna 215mm away from the central antenna. The excitation is sinusoidal modulated Gaussian pulse with a carrier frequency of 2.3GHz.

In order to highlight the shape, we normalize the absolute value to the maximum and obtain the channel character $H_{aa}(j\omega)$ is shown in Figure 3. In the figure, the amplitude of $H_{aa}(j\omega)$ is attenuated of about 3dB at the center frequency. We can see the scheme of antenna cancellation can have a suppression on self-interference.

Another scheme is shown in Figure 4. The distances between the TX and the RX are the same, but one TX is excited $T/2$ later than another. So the two signal send by transmit antennas will arrive at the receive antenna with a phase difference of π which just implements a cancellation.

In the space one can calculate, all the antennas are placed at the central part of the calculation space. The transmit antennas are 150mm away from the central antenna. The right antenna is excited $T/2$ later than the left. The excitation is sinusoidal modulated Gaussian pulse with a carrier frequency of 2.3GHz.

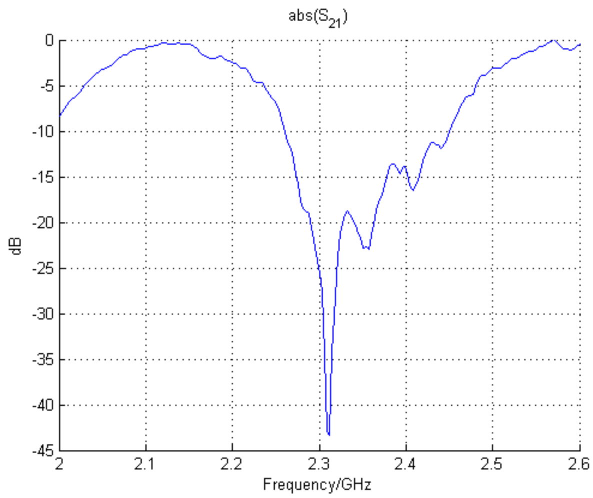

Figure 6. The channel tested with vector network analyze

The transmission characteristic is shown in Figure 5. The amplitude of $H_{aa}(j\omega)$ is attenuated of about 30dB at the center frequency more than the first scheme.

To prove this, an experiment is done like what has been shown in Figure 4. With the use of vector network analyzer, a similar result can be got shown in Figure 6.

We can see this scheme of antenna cancellation have a better effect on self-interference. However, the slope near the recess tends to infinite, in another words, the bandwidth of this scheme is extremely narrow, which prevents supporting wideband signals. Furthermore, the second scheme is particularly sensitive to the changes in environment. A small change that will make the operating point shift to an undesirable position.

C. Self-interference channel simulation

At first, in order to get the channel characteristics between the transmit antenna and receive antenna in free space, both the antennas are placed at the central part of the calculation space. The transmit antennas are 130mm away from the

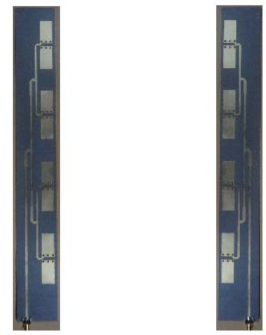

Figure 8. Antennas used for experiment

central antenna. The excitation is sinusoidal modulated Gaussian pulse with a carrier frequency of 3GHz.

Then an iron box is set behind the antennas with a distance of 300mm acted as a vector network analyzer. At the same time, at the bottom of the antennas, a wooden table was added covered the entire horizontal space. Comparing these two conditions, the channel between transmit and receive antennas shows different amplitude fluctuations at different frequencies.

Furthermore, the concrete walls are introduced in around the calculation space. The channel transfer function shown in Figure 7 becomes more ups and downs. As this trend, when the surrounding scatters become extremely rich, the transfer function will be quite similar with the actual.

D. Comparison of the results of experiment, commercial software and our program

To explore the effect of our program, a test is made that showed in Figure 8. Around the antennas some scatters are introduced at the same time.

With the use of vector network analyzer, one can clearly know the transmission characteristics S_{21} between TX and RX. Export data to MATLAB and the result is shown in Figure 9 with green solid line. The figure shows the center frequency of the antenna is 2.3GHz, and the bandwidth is about 1GHz.

Next, using a commercial software, a simulation model is created and solved and the result is shown in Figure 9 with

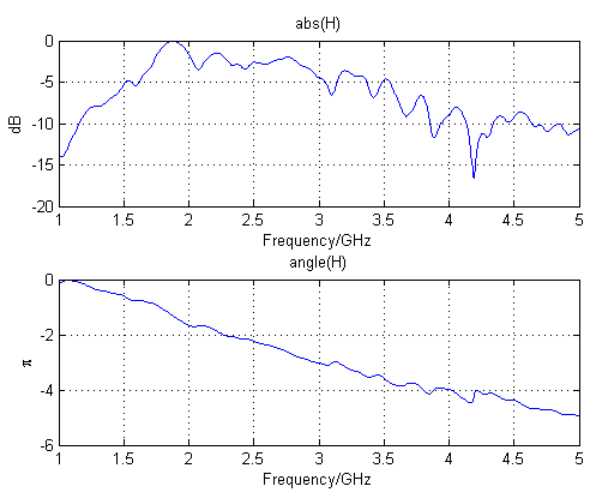

Figure 7. Channel with the presence of table, box and cement walls

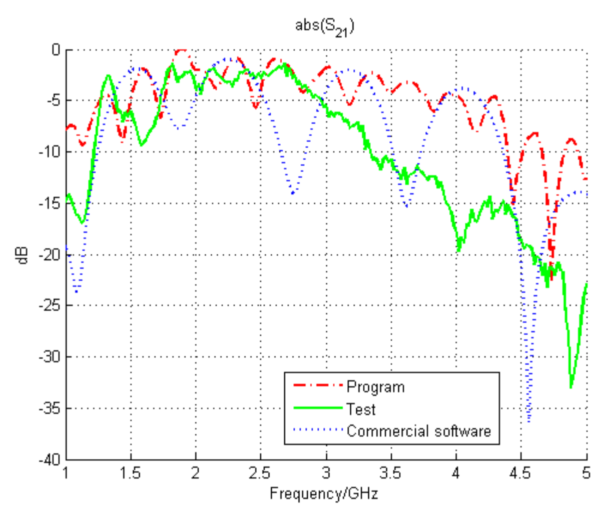

Figure 9. $|S_{21}|$ between TX and RX in scattering space

blue short dash line. From the figure, one can see the simulation result of this commercial software is different with the actual result and the central frequency are not the same.

Finally, using the program, set medium according to the real position. The excitation is sinusoidal modulated Gaussian pulse with a carrier frequency of 2.3GHz. The transmission characteristic is shown in Figure 9 with red dotted line. The figure graphs the simulation result of our program, which is the same with the actual result especially near the central frequency.

In conclusion, the program has a better simulation result near the central frequency. Using the program, the response between transmit and receive antennas is more similar to measurement result. With the assistance of the adaptive algorithm, a better self-interference suppression will be got.

IV. Conclusion

In order to promote the development of full-duplex systems it is important to have signal models. We try to contribute this area by providing a simplest model. We have showed the self-interference channel $h_{aa}(t)$ can be got in analog domain. Assistance with the adaptive algorithm, a better self-interference suppression can be got. With the combine of other techniques, a better full-duplex system will be used in the future doubling the resource utilization.

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