Lecture 12: Full Duplex Communication

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So far, we've discussed (and often assumed) that radios are half-duplex (meaning: can't transmit and receive at the same time), based on the assumption that self interference is an unsolvable constraint. This assumption has changed in the last couple of years. We consider 'Full-duplex' as radios that are able to Tx/Rx at the same time.

We notice that RFID is full-duplex due to short range and low bitrate.

Circulator - Classical approach is to isolate transmitter and receiver. This is combined with a circulator, schematically represented in Fig. 1. The signal can go from 1 to 2, 2 to 3, and 3 to 1. Notice that the transmit ideally does not bleed from 1 to 3. It can only achieve around 25-30dB of isolation, which is not enough (req 100dB). This is, however, sufficient for RFIDs.
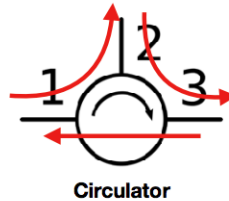

Figure 1: Schematic representation of an analog circulator.

1 Technique #1: Digital Cancellation

Subtract in the signal domain (similar to ZigZag). Suppose that x_1 is being transmitted and x_2 is attempting to be received. The antenna receives $y = h_2 x_2 + h_1 x_1$, where $h_1 x_1$ is self-interference and $h_2 x_2$ is external.

$$
\begin{aligned}
< y, x_1 > &= \sum (h_2 x_2 + h_1 x_1) x_1^* \\
&= h_2 \sum \cancel{x_2 x_1^*} + h_1 \sum x_1 x_1^* \\
&= h_1 \sum \|x_1\|
\end{aligned}
\tag{1}
$$

This allows us to estimate $\hat{h_1}$., To recover x_2, simply compute . . .

$$
h_2 x_2 = y - \hat{h_1} x_1
\tag{2}
$$

where $\hat{h_1}$ is the estimated self interference channel.

This is still not enough cancellation, because ADC does not have enough dynamic range. The analog to digital converter (ADC) converts a continuous analog signal $y(+)$ to a discrete digital signal $y[n]$. The result is encoded in a number of bits (usually 8-12bits). There is a finite resolution of bits to allocate what is being received. In half-duplex, all the bits are allocated to receiving the external signal. In full duplex (with limited interference suppression), some of the bits are allocated to the external signal but a lot is also receiving self-interference. This is depicted in Fig. 2.
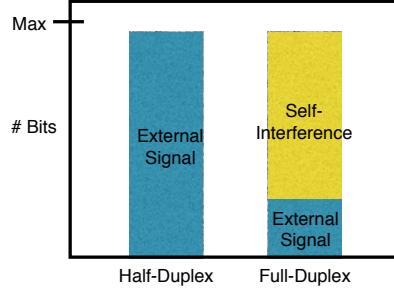

Figure 2: The range of bits measured by the ADC for half- and full-duplex transmission, scaled due to the AGC.

This can be seen also in the analog space. When just receiving an external signal, the automatic gain control (AGC) scales this signal to the full analog range (range of bits). With self-interference, this adds significantly to the external signal. To avoid saturating this range, the ADC scales the resolution down to 'fit' this signal. But this lowers the amount of signal corresponding to each incremental bit.

2 Technique #2: Antenna Cancellation

This technique is used in the MobiCom '10 paper.

The two transmitting antennas are separated by d and $d + \lambda/2$ on either side of the receiving antenna, depicted in Fig. 3.
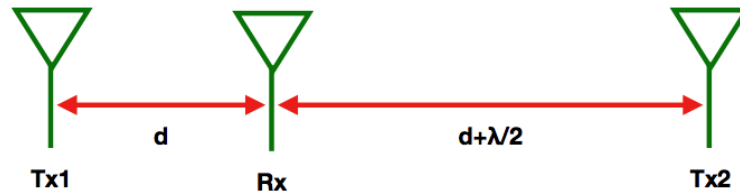

Figure 3: Antenna setup.

The receiving antenna senses $x(t)$ from Tx1 with transformation h_1 and from Tx2 with transformation h_2. Equation 3 describes how the receiving antenna cancels the effect of the transmitting antenna. This affect is due to the physics of the setup rather than any processing.

$$
\begin{aligned}
\texttt{Tx1:} & \, x(t) \\
\texttt{Tx2:} & \, x(t) \\
\texttt{Rx:} \, y(x) &= h_1 x(t) + h_2 x(t) \\
&= (h_1 + h_2)x(t) \\
&\approx \left(e^{-j2\pi d/\lambda} + e^{-j2\pi(d+d/2)/\lambda} \right) x(t) \\
&\approx e^{j2\pi d/\lambda}(1 + e^{-j\pi})x(t) \\
&= 0
\end{aligned}
\tag{3}
$$

Problems:

- This works in the narrowband (20MHz), but is not practical with wider bands (ex. OFDM).

- Multipath is not accounted for, since this only cancels out direct path.

- Requires 3 antennas for one receive.

- Requires exact placement of antennas.

- Assumes only linear cancellation

Components like amplifiers/wires/antennas lead to non-linearities. Although you transmit $x(t)$, it is actually $x(t) + ax^2(t) + bx^3(t) + \ ....$

3 Technique #3: Non-linear Cancellation

The idea is to approximate the the non-linear response (encompassing constants a, b, etc. above) and subtract the self-interference.

Problem: This still does not improve multipath and is limited to narrowband transmission.

Solution: Sum up multiple attenuation (A) and delay (D) blocks at transmitting antenna. Each A and D block pair is actually one FIR filter. You train the FIR filters based on known signals, since these blocks are programmable.

Changes from MIMO to SISO So far, this applied to SISO. When moving to MIMO, there is cross-talk, meaning that every transmitter will leak into every other receiver. The cancellation circuit from before can be replicated N^2 for N antennas, but this is power hungry and space consuming. Alternatively, the number of cancellation circuits can be reduced by the realization that the self-interference from one antenna is very similar (with offset) to the cross-talk affecting another. The self-interference is much much larger than the cross-interference. The signal from one antenna is passed to the other's cancellation blocks to remove its effect. This method is cascaded for each of the antennas for the full cancellation system.
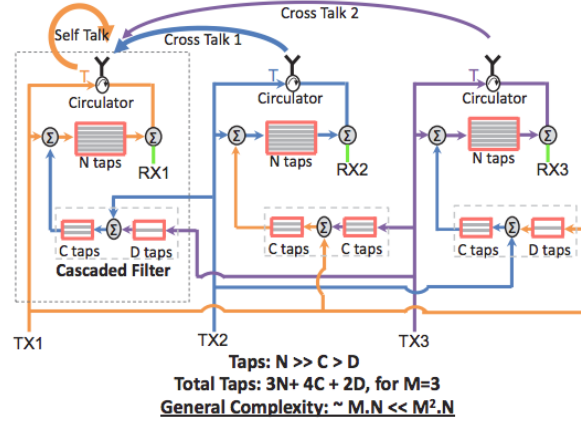
Figure 4: Condensed overview of MIMO cancellation technique.

4   Applications

4.1   Hidden Terminal Problem

A transmits to B, and C wants to transmits to B also. A and C cannot hear one another, so A and C transmit at the same time and collide at B. With full duplex, C can hear B and stop transmitting.

4.2   Reduce Latency in Multihop

The middle node (B) is a full-duplex relay, so it can transmit as its receiving. With half-duplex, B is receiving/transmitting 50/50 of the time.

References

[1] Li, N., Zhu, W., Han, H. (2012). Digital Interference Cancellation in Single Channel, Full Duplex Wireless Communication. *2012 8th International Conference on Wireless Communications, Networking and Mobile Computing.* doi:10.1109/wicom.2012.6478497

[2] Bharadia, D.,   Katti, S. (2016). Full-duplex Radios. *Towards 5G*, 365-394. doi:10.1002/9781118979846.ch16