Impact of Phase Noise on Full Duplex Wireless Systems

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Outline

Outline

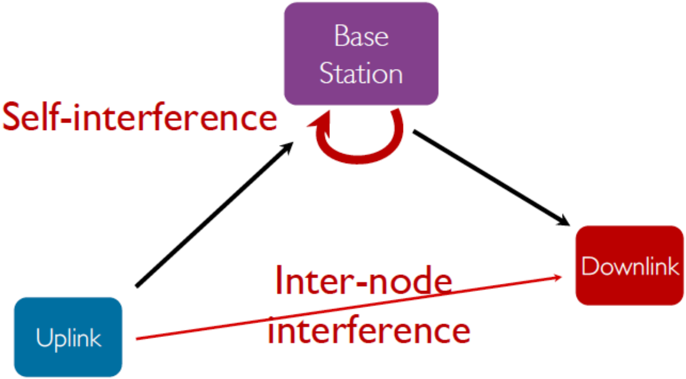


Figure 1: Full Duplex Base Station Topology [3]

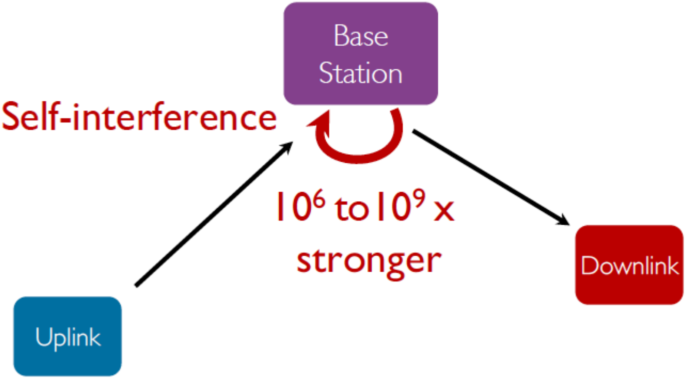
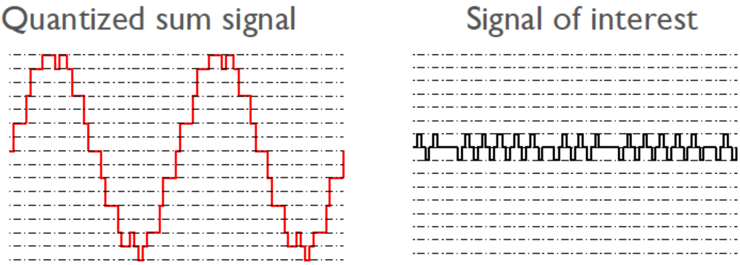


Figure 1: Full Duplex Base Station Topology [3]

Self-Interference Bottleneck

Digital Cancelation alone is insufficient : Signal of Interest swamped



Need to reduce strength of self-interference before ADC

Self-Interference Bottleneck

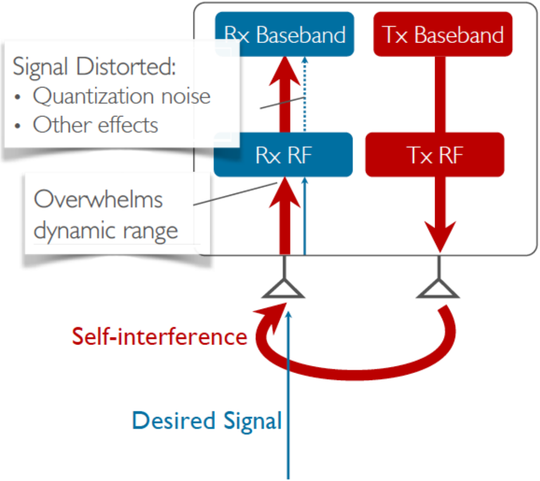


Figure 2: Representation of Self-Interfernce bottleneck at Rx-RF and Rx-Baseband [3]

Outline

Methods of Reducing Self-Interference

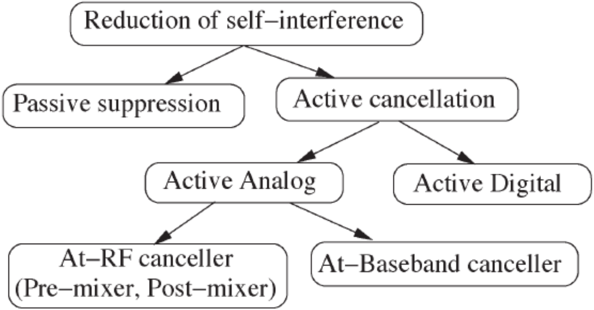


Figure 3: (Fig.1 [6]) Classification of methods of reducing self-interference

Methods of Reducing Self-Interference

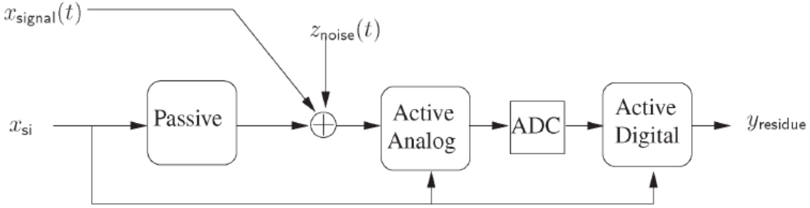


Figure 4: (Fig.2 [6]) Block diagram representation of all the self-interference reduction methods in concatenation.

Outline

Narrowband Signal Model

The received signal at Node 1 denoted by $y(t)$

$$y(t) = h_{si}x_{si}(t - \Delta_{si}) + h_s x_s(t - \Delta_s) + z(t) \tag{1}$$

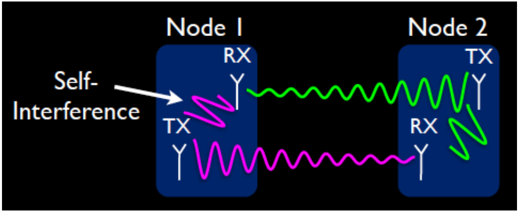


Figure 5: Representation where Node 1 and 2 are full duplex

Amount of Cancelation

Given an estimate of the self-interference channel, $\hat{\boldsymbol{h}}_{si}(t) = \hat{h}_{si}(t - \hat{\Delta}_{si})$, a cancelling signal, $x_c(t) = \hat{h}_{si} x_{si}(t - \hat{\Delta}_{si})$ can be generated. Adding the cancelling signal to the received self-interference signal results in a residual

$$y_{res}(t) = h_{si} x_{si}(t - \Delta_{si}) - \hat{h}_{si} x_{si}(t - \hat{\Delta}_{si}) + z(t) \tag{2}$$

Let a training sequence $[s_1, s_2, ...s_{train}]$ of length T_{train} , with $\mathbb{E}(|x_{si}(t)^2) \leq 1$, where $i \in \{1, 2, ..., T_{train}\}$ be used to obtain the estimate, $\hat{h}_{si}(t)$ of the self-interference channel. Then,

$$\mathbb{E}(|y_{res}|^2) < \frac{5\sigma_z^2}{T_{train}} + \sigma_z^2 \tag{3}$$

1. From (3), the residual should decay inversely with the length of training sequence
2. For $T_{train} = 5$, the residual self-interference is no more than 3 dB above thermal noise
3. In [1], however, the residual self-interference is 15 dB higher than the thermal noise which is clearly not explained by the signal model in (1)

Raising a possibility of some other source of impairment leading to a bottleneck in active cancellation !!

Outline

Experiment

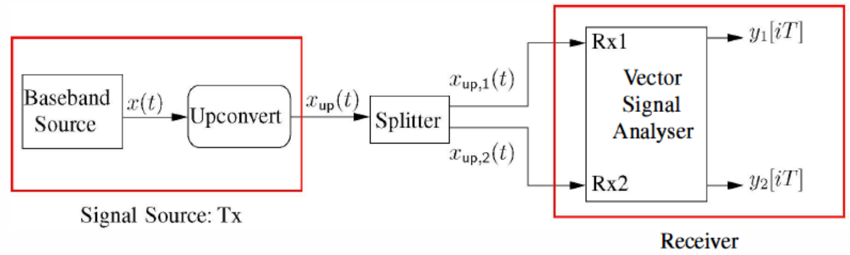


Figure 6: Schematic of the experiment to acquire copies of a signals using a VSA. WARP and vector signal generator were two different signal sources considered in the experiment.(Fig.1 [5])

Experiment

The received sequences can be written as

$$y_1[iT] = h_1 e^{-j(w_c+w)\Delta_1} x[iT] + z_1[iT] \tag{4}$$

$$y_2[iT] = h_2 e^{-j(w_c+w)\Delta_2} x[iT] + z_2[iT] \tag{5}$$

Mimicking active cancellation by subtracting a scaled and delayed version of the $y_1[iT]$ from $y_2[iT]$. The residual after active cancellation will be

$$y_{res,d}(iT) = y_2[iT] - h(d) y_1[(i-d)T] \tag{6}$$

the scaling is computed as

$$h(d) = \frac{\sum_{i=1}^{N} y_2[iT]' y1[(i-d)T]}{\sum_{i=1}^{N} |y_2[iT]|^2} \tag{7}$$

Experiment

As $N \to \infty$

$$\mathbb{E}(|y_{res,d}[iT]|^2) = \frac{|h_1|^2}{|h_2|^2}\sigma_z^2 + 2\sigma_z^2 \tag{8}$$

For the experiment conducted $\frac{|h_1|^2}{|h_2|^2} \approx 1$, thus it is expected that strength of the residual self-interference should be approximately $3\sigma_z^2$ a quantity independent of the delay d.

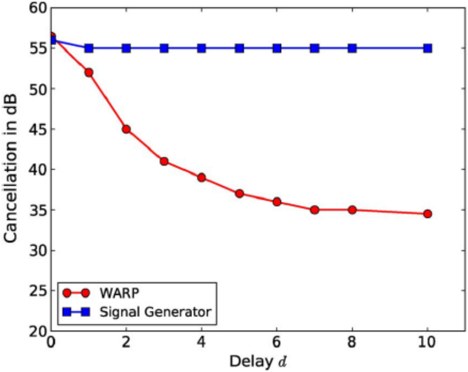


Figure 7: Amount of cancelation as a function of the delay for different signal sources measured from the experiment (Fig.5 [6])

Phase noise explains trend of cancelation

In presence of phase noise, the equations (4) and (5) can be rewritten as

$$y_1[iT] = h_1 e^{-j(w_c+w)\Delta_1} e^{j\phi[iT-\Delta_1]} x[iT] + z_1[iT] \tag{9}$$

$$y_2[iT] = h_2 e^{-j(w_c+w)\Delta_2} e^{j\phi[iT-\Delta_2]} x[iT] + z_2[iT] \tag{10}$$

The residual self-interference will be

$$\begin{aligned} y_{res,d}[iT] \approx jh_1 x[iT] e^{-j(w_c+w)\Delta_1}(\phi[iT-\Delta_1]- \\ \phi[iT-\Delta_2-dT]) + z_1[iT] - z_2[(i-d)T], \end{aligned} \tag{11}$$

Phase noise explains trend of cancelation

The resulting strength of the residual self-interference is

$$\mathbb{E}(|y_{res,d}[iT]|^2) = 2|h_1|^2\sigma_\phi^2(1 - R_\phi(dT)) + 2\sigma_z^2$$

Observations:

1. As the delay increases, it is natural that the temporal correlation in phase noise reduces.
2. Once the delay is sufficiently large, $R_\phi(dT)) \approx 0$, thus the dependence of the residual on delay will vanish.

Outline

Q1: What limits the amount of active analog cancelation in a full duplex system design?

Impact of Phase noise on Active Analog Cancelation

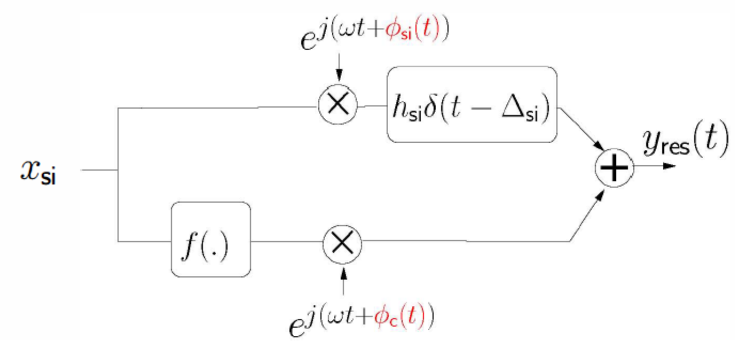


Figure 8: (Fig.3 [5]) Block diagram representation of the active analog canceller used in [1, 2]

Impact of Phase noise on Active Analog Cancelation

- The objective of the active analog canceller is to create a null for the self-interference.
- If the cancelling filter $f(t) = -h_{si} e^{-jw\Delta_{si}} \delta(t - \Delta_{si})$ then the cancelling signal is $x_c(t) = -h_{si} e^{-jw\Delta_{si}} x_{si}(t - \Delta_{si})$.
- After upconversion, the cancelling signal is given by $x_c(t) e^{j(w_c t + \phi_c(t))}$ and once the cancelling signal is added to the received self-interference signal, then the residual self-interference is given by

$$y_{res}(t) = h_{si} e^{jw_c(t-\Delta_{si})} x_{si}(t - \Delta_{si})(e^{j\phi_s(t-\Delta_{si})} - e^{j\phi_c(t)}) + z(t) \quad (12)$$

Result 1

The strength of the residual self-interference signal can be estimated as

$$\mathbb{E}(|y_{res}(t)|^2) \overset{(a)}{\approx} |h_{si}|^2\, \mathbb{E}(|\phi_{si}(t-\Delta_{si}) - \phi_c(t)|^2) + \sigma_z^2 \tag{13}$$

$$\overset{(b)}{=} 2|h_{si}|^2\sigma_{si}^2 + \sigma_z^2 \tag{14}$$

The amount of cancellation is the ratio of the strength of self-interference before cancellation to the strength of self-interference after cancellation which is $\frac{|h_{si}^2}{2|h_{si}^2\sigma_{si}^2+\sigma_z^2} \leq \frac{1}{2\sigma_{si}^2}$, where $\mathbb{E}(|\phi_{si}(t)|^2) = \mathbb{E}(|\phi_c(t)|^2) = \sigma_{si}^2$

Result 1

The amount of active analog cancelation is limited by the inverse of the variance of phase noise. Moreover, matching local oscillators in the self-interference and canceling paths can increase the amount of active analog cancelation.

Outline

Q2: How do the numbers of cancelations by active analog and digital cancelers depend on each other in a cascaded system?

Benefit of Digital cancellation after Active Analog Cancelation

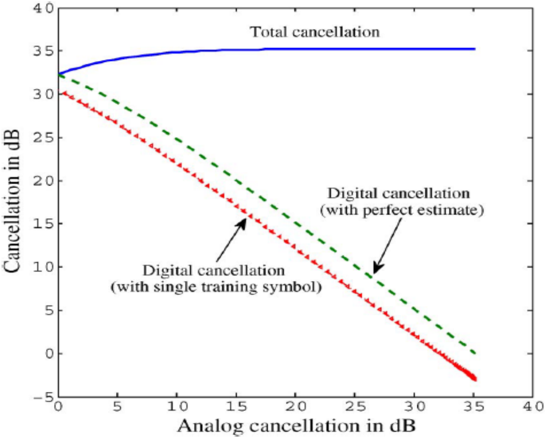


Figure 9: (Fig.8 [6]) Relationship between amount of active analog cancelation and the amount of digital cancelation is shown.

Benefit of Digital cancellation after Active Analog Cancelation

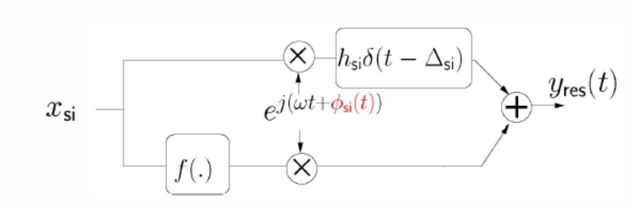


Figure 10: (Fig.5 [5]) Active analog canceller with matched local oscillator

Let $\hat{\boldsymbol{h}}_{si}(t) = \hat{h}_{si}(t-\tau)$, where $(\Delta_{si}-\tau)$ denotes the error in the knowledge of delay. Then, the residual self-interference in digital baseband is given by

$$y_{res}(iT) \approx h_{si} e^{-j(w\Delta_{si}+\phi_c[iT]-\phi_d[iT])}(x_{si}[iT-\Delta_{si}]-x_{si}[iT-\tau] + x_{si}[iT-\Delta_{si}](\phi_{si}[iT-\Delta_{si}-\phi_c(iT))+z(iT) \quad (15)$$

Benefit of Digital cancellation after Active Analog Cancelation

- The strength of the residual self-interference before digital cancellation is $2|h_{si}|^2(1 - R_{\phi_{si}}(\Delta_{si} - \tau) + \sigma_\phi^2) + \sigma_z^2$.
- The digital canceller signal is $-h_{si}e^{-jw\Delta_{si}}(x_{si}[iT - \Delta_{si}] - x_{si}[iT - \tau])$
- After digital cancellation, the strength of residual self-interference is $2|h_{si}|^2((1 - R_x(\Delta_{si}) - \tau)(\sigma_{si}^2 + \sigma_d^2) + \sigma_\phi^2) + \sigma_z^2$.
- Digital cancellation manages to cancel only the part of the residual self-interference which is correlated to the selfinterference signal itself. The sum total of active analog and digital cancellation is upper bounded by $\frac{1}{2\sigma_{si}^2}$.

Result 2

The sum total of the amount of cancellation, for serially concatenated active analog and digital stages of cancellation, is bounded above by the inverse of the variance of phase noise of the local oscillators.

Outline

Q3: How and when does passive suppression impact the amount of analog cancelation?

Influence of Passive Suppression on Active Cancelation

Result 3

Higher passive suppression can result in lower active analog cancelation. However, increasing passive suppression implies that the sum of cascaded passive and active analog cancelation increases.

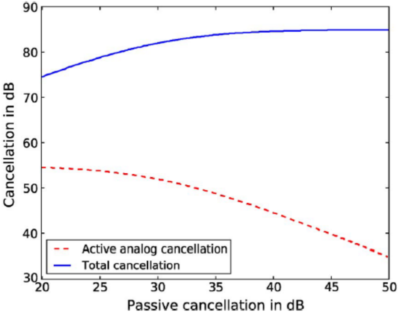


Figure 11: (Fig.9 [6]) Total cancelation represents the sum of passive and active analog cancelation when operated in cascade

Outline

Conclusion

- This study provided an analytical explanation of experimentally observed performance bottlenecks in full-duplex systems
- The analysis clearly shows that phase noise is a major bottleneck in current full-duplex systems and thus reducing the phase noise figure of radio mixers could lead to improved self-interference cancelation.

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