Two Technologies Being Considered for 5G PHY Layer

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Technology 1: In-Band Full Duplex (IBFD) Communications
Introduction

- Full Duplex wireless communications based on self-interference cancellation have been attracted attention in recent years.
- Its operation principle is very similar to the decades-old echo-cancellation full duplex wireline modems with some differences due to the operating environment.
- In this presentation, their similarities and differences will be presented.
- The theoretical achievable cancellation performance will be summarized.
- The possible applications and the limitations of this technique are discussed.
Full-Duplex Wireless Communication with Self-Interference Cancellation

- Coding/Modulation
- DAC Up-conversion/Filtering/RF-PA
- Analog Canceller
- LNA/Down-conversion/Filtering/ADC

Tx Data → Coding/Modulation → DAC Up-conversion/Filtering/RF-PA → Analog Canceller → LNA/Down-conversion/Filtering/ADC → Rx Data

Tx Symbols → Demod./digital echo canceller/decoding → Analog Canceller

Tx Signal → Direct path

Self Interference → Reflected paths

Rx Data → Demod./digital echo canceller/decoding → Rx Signal
Echo Cancellation Wireline Modem

Complex Tx Symbols

Tx Filter/Modulator

DAC/low-pass filter

Hybrid coupler

Transmission Line

Near Echo Leakage

Bandpass filtering/IQ splitting/demodulation

Far-end Echo

Bulk delay line

Near echo canceller

Far echo canceller

To other receiver blocks

Timing recovery

Timing rate conversion

Sampled at 2xTx clock

At Rx clock

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Commonalities and Differences

• Commonalities:
  – The main objective is to remove the leaked Tx signal from the Rx signals
  – Need isolations between the Tx and Rx signals to reduce the self-interferences in the Rx signals
  – The residual interference are removed by interference cancellation techniques
    • The replica of interference signals are synthesized using known Tx signal and emulated interference channel
    • The synthesized interference are subtracted from the Rx signal
    • Input data are known uncorrelated Tx symbols
    • Achievable cancellation is mainly determined by the accuracy of channel estimation
  – Non-linearity is the main limiting factor
Commonalities and Differences (cont.)

• Differences:
  – The isolation can be more effective in wireless systems if using separate Tx and Rx antennas is feasible
  – Non-linearity is usually more severe in wireless systems
    • High power RF amplifier has high non-linearity
    • Reduction of phase-noise is also difficult in such systems
    • Analog canceller may be able to cancel part of such non-linear interferences
  – Wireless channel always has some time variation
    • It is true even for the self-interference channels
    • Time variation imposes another limit to the channel estimation accuracy
Cancelation limit due to time variation (cont.)

• Consider LMS or RLS algorithms for channel estimation
  – For static channel the estimator is optimal
  – For complex sinusoid variation with frequency $\omega_0$:
    $$\left|1 - H(e^{j\omega_0})\right|^2 \approx \frac{(1 - \mu)^2 \omega_0^2}{(2 - \mu)^2 \omega_0^2 / 4 + \mu^2}$$
    • For general fading case, error can be computed by integration over the Doppler spectrum
    • 20 dB cancellation improvement for 10 times lower frequency
  – The reduction speed is not very fast because
    • High cancellation requirement
    • is usually very small, e.g., $10^{-3}$ to $10^{-5}$, for small excess MSE at high receiver SNR
• Channel variation will impose a limit in achievable cancellation even at very low frequency, e.g., 0.05Hz
Concluding Remarks

• Total achievable cancelation may be expressed as:
  \[ R_{c_{total}} \leq \min[(R_{NL} + R_{NL\text{-}compensation}), R_{ch\text{-}var}] + R_{Isolation} \]
  – The first term would be in the range of 30-60 dB
  – Isolation gain depending on the environment and possible antenna arrangement

• IBFC is most suitable for
  – applications when the channel attenuation is not too high, e.g.
    • for point to point systems, small cells, and/or
    • on the base station side.
  – It will be a challenge in high propagation loss and in complex environments, e.g., cellular system and handheld devices

• It is most important to check achievable cancellation before deciding its possible applications

• It’s not a miracle formula for doubling system capacity
Technology 2: Faster Than Nyquist (FTN) Signaling
FTN History and Today

• The concept of FTN was first introduced in a BSTJ paper by Jim Mazo in 1975.

• It has attracted attention in academia and industry lately.
  – Academia: Most earlier researches were done by researchers in Lund University, Sweden
  – Industry, it has been viewed as one of the candidate technologies for 5G PHY layer
  – References
Model of Band-Limited Communication Channel

- Overall baseband channel response in a communication system

\[ x(t) = \sum_{n=-\infty}^{\infty} a_n f_T(t - nT) \]

- Receiver waveform:
  \[ y(t) = \sum_{m=-\infty}^{\infty} a_m g_{ch}(t - mT) + z(t) \]

- Overall channel response:
  \[ g_{ch}(t) = f_T(t) * h(t) * f_R(t) \]

where: \( a_n \) – Tx data symbols, \( T \) – symbol duration, \( h(t) \) – channel impulse response, \( z(t) \) – additive Gaussian noise in \( y(t) \)

For band-limited channels, the baseband frequency response of \( g_{ch}(t) \), satisfies: \( G_{ch}(\omega) = 0 \), for \( |\omega| > B_{ch}/2 \), where \( B_{ch} \) is channel bandwidth
ISI Free Channel – The Nyquist Criterion

• To recover the transmitted symbol $a_n$, the output of the composite channel is sampled at $nT$, which can be expressed as:

$$y(nT) = \sum_{m=\infty}^{\infty} a_m g_{ch}(nT - mT) + a_n g_{ch}(0) + z(nT)$$

  – The summation on the right side contains the ISI terms
  – In order for the sampled output is a good estimate of , it is desirable that the ISI terms are all equal to zero, ISI Free

• The channel is ISI free, if and only if $G_{ch}(f)$, the Fourier transform of $g_{ch}(t)$, satisfies:

$$\sum_{k=\infty}^{\infty} G_{ch}(f - \frac{k}{T}) = const, \text{ for } -\frac{1}{2T} \leq f < \frac{1}{2T}$$

Namely, the aliased spectrum is a constant. We call such a channel satisfying the Nyquist Criterion
The Nyquist Criterion (cont.)

- Common $G_{ch}(f)$ satisfies the Nyquist Criterion:
  - Brick-wall spectrum: $G_{ch}(f) = 1$ for $|f| \leq 1/T$, $G_{ch}(f) = 0$ for $|f| > 1/T$
  - Raised Cosine spectrum
    \[
    G_{ch}(f) = \begin{cases} 
    1 & \text{for } |f| \leq (1 - \beta) / T, \\
    0 & \text{for } |f| > (1 + \beta) / T \\
    \frac{1}{2} \cos(f - 1 + \beta + 1) & \text{for } (1 - \beta) / T < |f| \leq (1 + \beta) / T 
    \end{cases}
    \]
- Channel bandwidth: $-(1 + \beta) / T \leq f < (1 + \beta) / T$

- There are other spectrum shapes satisfy the Nyquist Criterion

- After sampling at $1/T$, the aliased signal spectrum has a width of $B = 1/T$ and its magnitude is a constant

- The non-brick-wall spectrum occupies a frequency band that is larger than $1/T$
Faster than Nyquest (FTN) Signaling

- Generation of faster than Nyquest (FTN) signaling
  - Data symbols, $a_{n,FTN}$, are generated at $1/T_d$, $T_d = \tau T$, $\tau < 1$, to yield an train of impulses spaced at every $T_d$, i.e. at the rate of $1/T_d > 1/T$.
  - The impulse train is filtered by a low-pass filter $g_{FTN}$ with a frequency response $G_{FTN}(f) = 0$, for $|f| > (1 + \beta) / 2T$
  - This signaling does not satisfy Nyquist criterion for sampling rate of $1/T_d > 1/T$
    - There will be ISI of the data symbols

- FTN Receiver of FTN signaling
  - Signal is sampled at $1/T_s$ for $1/T_s > 1/(1+\beta)T > 1/T$
  - Traditional equalization techniques can be used to recover $a_{n,FTN}$. 
Capacity of FTN signaling

• As shown by the researchers at Lund University, Sweden, FTN has a higher channel capacity than Nyquist signaling.

• Channel capacity for Nyquist signaling is

\[ C = \log_2 \left( \frac{SNR + 1}{T} \right) = \log_2 \left( \frac{P_s / N_0 + 1}{T} \right) \]

with overall channel response satisfies Nyquist criterion.

• Channel capacity for FTN signaling

\[ C_{FTN} = \int_{-\infty}^{\infty} \left[ SNR(f) + 1 \right] df = \int_{-\infty}^{\infty} \left[ P_s |G_{FTN}(f)|^2 + 1 \right] df \]

  – if \( \int_{-\infty}^{\infty} |G_{FTN}(f)|^2 df = 1 \), the total signal power remain the same, as in the Nyquist case.

  – Assuming he noise power spectrum is also the same, i.e., the power spectrum density is is a constant \( N_0 \)
Remarks

• The advantage of FTN relative to Nyquist signaling in single carrier systems is that it can better utilize the transition band spectrum

• How much better needs to be further evaluated

• From the analytical formula given above, the gain is higher when bits per Hz is large, i.e., at high spectrum efficiency regions.
  – Around 10 bits/symbol, a gain of 2 dB is possible.
    • This is equivalent to less than 7% of throughput gain
  – The gain will be much less for fewer bits per symbol

• It also makes timing synchronization more difficult

• FTN has been demonstrated to be more robust to the non-linearity effects in the Tx/Rx path.

• Is it worth it?