In-band Full-duplex Wireless Communications – from Echo-cancellation to Self-interference Cancellation

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OUTLINE

- Overview of In-band *Full-duplex Communication* (IBFC)
- From Echo-cancellation to Self-interference Cancellation
- Characteristics of Echo/Self-interference Cancellers
- IBFD's Achievable Performance Evaluation and Possible Applications
- Concluding Remarks and Potential Research Areas

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OVERVIEW OF IN-BAND *FULL-DUPLEX COMMUNICATION* (IBFC)

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What Is In-Band Full-Duplex Communications

- Historically, wireless systems use different frequency bands (FDM) or time slots (TDM) for forward and reverse link communications
- The same frequency band are used for the two links at the same time because the transmitted signal interferes the received signal
  - Such interference is called *Self-Interference*
- The In-Band Full-Duplex (IBFD) method reduces the interference of the transmitted signal to the received signal to achieve full-duplex operation by
  - Spatial isolation and
  - Self-interference cancellation

Why and When to Use IBFD

- It has generated a lot of interest in wireless communications recently because
  - IBFD have the potential to double spectrum efficiency to meet the increasing demand of wireless communications
  - Due to the advance in communication and computer engineering, processing power is greatly increased and could fit in the physical dimensions of wireless devices
  - The recent trend of wireless communication is towards near field from far field
    - Smaller link loss to make IBFD possibly feasible
- However, IBFD has its limitations
  - We need to understand the limitations to determine what are its possible applications
  - It is not a magic formula to double spectrum efficiency

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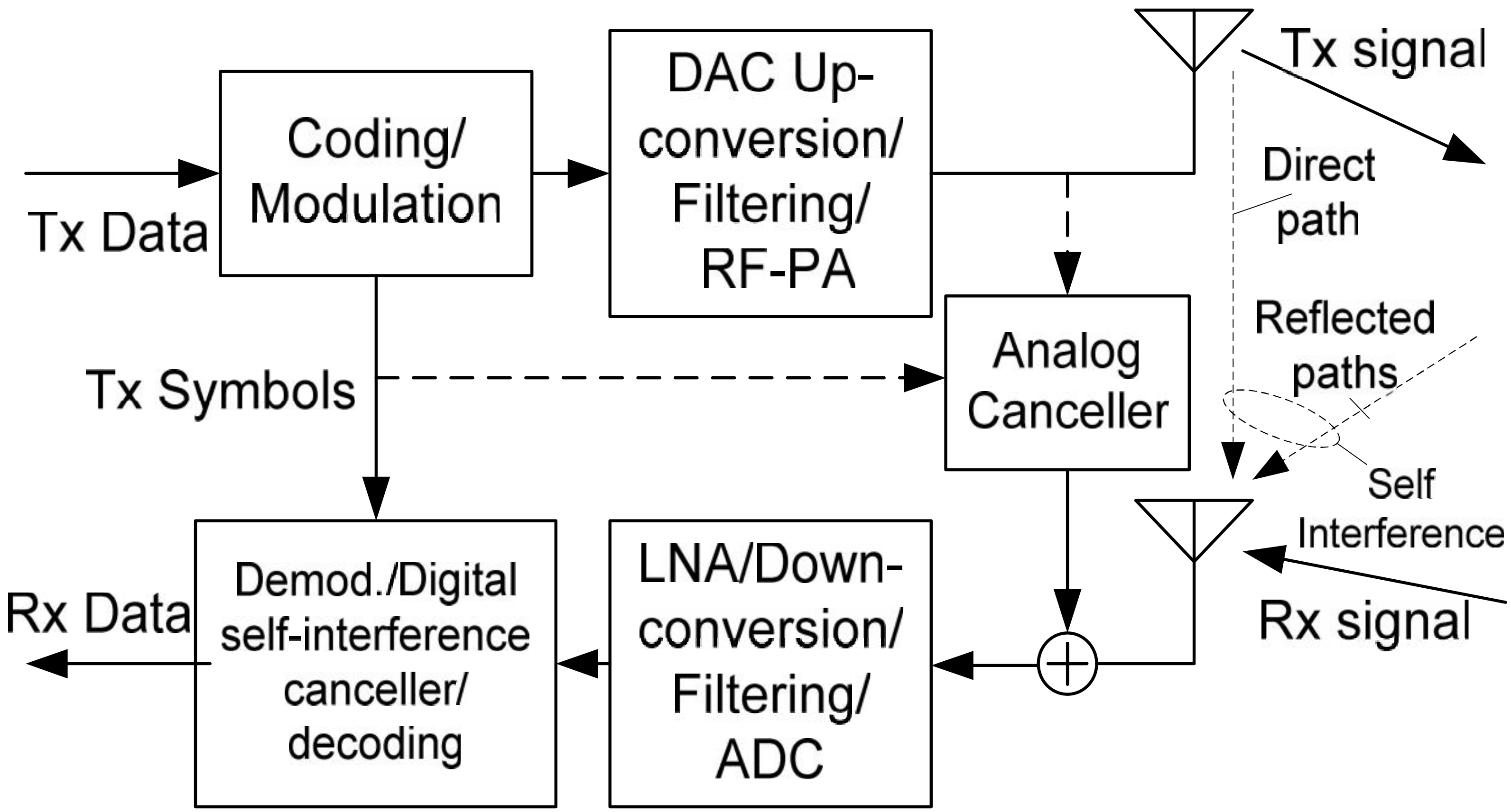
Full-Duplex Wireless Communication with Self-Interference Cancellation (SIC)



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Key Components and Features of IBFD

- In a wireless system, the Tx signal interferes the Rx signal through direct paths and reflected paths.
- The self interference is reduced in RF by Tx/Rx isolation
  - Spatial isolation (beam-forming) in multi-antenna systems
  - Using circulator (similar to hybrid coupler) in single antenna systems
- The residual self interference is further reduced by self-interference canceller (SIC)
- SIC can be implemented in analog and/or digital forms
  - The analog SIC is for facilitating digital SIC implementations, e.g., ADC word length
  - It can also compensate for some of the non-linear effects
- Linear SIC cannot do better than the non-linear effects in the interferences

Predecessors of IBFD Wireless Communications

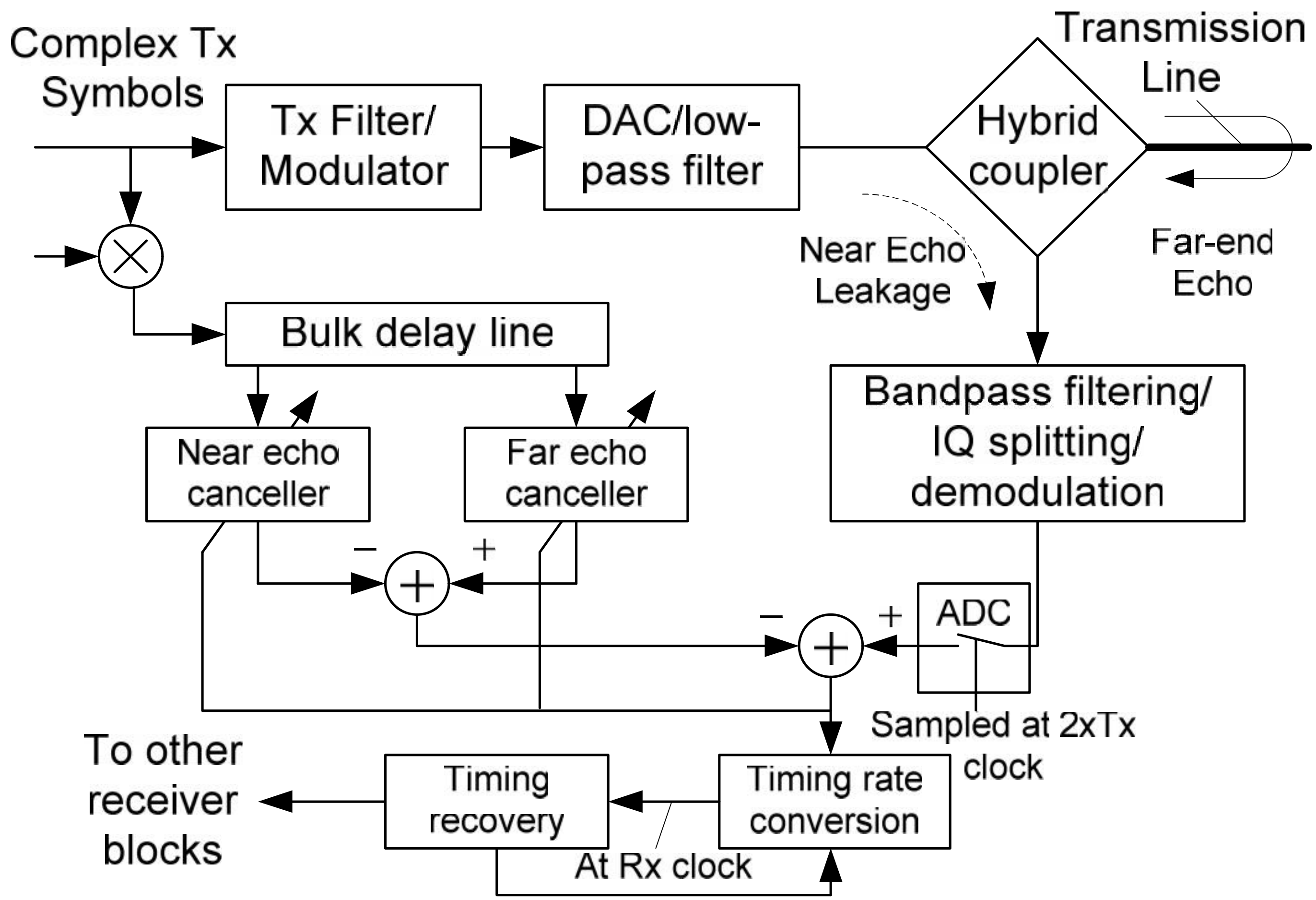
- Predecessor 1: IBFD in radar systems
  - This concept has been used in radar systems since 1940’s
  - The isolation between the Tx and Rx signals are achieved by
    - Reduction of the leaked Tx signal back to the Rx side by antenna beam forming in a multiple antenna systems
    - Using *Circulators* in a single antenna system to isolate Tx/Rx signals
    - Analog self-interference cancellation in 1960’s
- Predecessor 2: Echo cancellation in wireline modems
  - Echo Cancellation (EC) technology has been widely used in commercial wireline modems since 1980’s
  - The reduction between the Tx and Rx signals are achieved by using hybrid coupler and adaptive echo canceller
  - Many techniques developed and understood for EC technology are directly applicable to IBFD wireless systems

FROM ECHO-CANCELLATION TO SELF-INTERFERENCE CANCELLATION

The Echo Cancellation Technology

- Echo cancellation technology was developed since 1960's
- The wireline communication products employing EC has been commercialized since mid 80's
- The reduction of the Tx signal coming into the Rx signal (echo) is achieved by adaptive echo-canceller after initial attenuation using hybrid coupler
- Echo cancellation technology has been studied carefully by researchers and engineers over decades
- EC and SIC has many commonalities
- The result of such studies on EC can be directly applied to IBFD and provide guidance for IBFD system development
- We shall discuss their similarities and differences

Echo Cancellation Wireline Modem



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Key Components and Features of EC

- Hybrid coupler can create about 6-15 dB echo reduction
- The residual echo is reduced or eliminated by EC
- Characteristics of the echo
  - Echo can be modeled by known transmitted symbol convolved with the echo channel
    - In modem signals there are near and far echo components
  - The echo can be emulated by convolving the *known* Tx symbols with accurately estimated echo channel and known
  - Echo in the received signal can be removed by subtracting the emulated echo from the Rx signal
  - If the channel is truly linear and the channel estimate is accurate, echoes can be perfectly eliminated
  - Non-linearities in echoes are the main limiting factor
  - It is difficult to achieve echo cancellation of over 70 dB

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Key Components and Features of EC (cont.)

- Echo canceller implementation considerations
  - Received signal is sampled at T_{Tx}/M (usually, M = 2)
  - EC is has M (independent) sub-cancellers
  - EC has a tapped delay line (TDL) structure
  - The adaptive EC estimates the channel using LMS algorithm
  - The estimation accuracy, which determines the achievable EC ratio, is controlled by the adaptation step size
- Rate conversion
  - After echo cancellation the sampling rate need to be converged to synchronize with T_{Rx} for receiver functions
  - The rate conversion can be done by analog or digital means
- All of these features discussed are applicable to the self-interference cancellation of IBFD wireless systems

EC/IBFC – Commonalities and Differences

- Commonalities:
  - The main objective is to remove the leaked Tx signal from the Rx signals in both cases
  - 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 estimated/emulated interference channels
    - LMS algorithm is used for channel estimation/interference cancellation
    - 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

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Commonalities and Differences (cont.)

- Differences:
  - Isolation can be achieved more effectively 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 already existed in the RF (Tx) signal
    - Non-linear modeling of the Tx signal may be used to improve further SIC performance
  - Wireless channels always have some time variations
    - It is true even for the self-interference channels
    - Time variation imposes another limit to the channel estimation accuracy
  - Due to high sampling rate in SIC, it is more difficult to employ high precision ADCs resuling the need of analog canceller

CHARACTERISTICS OF ECHO/SELF-INTERFERENCE CANCELLERS

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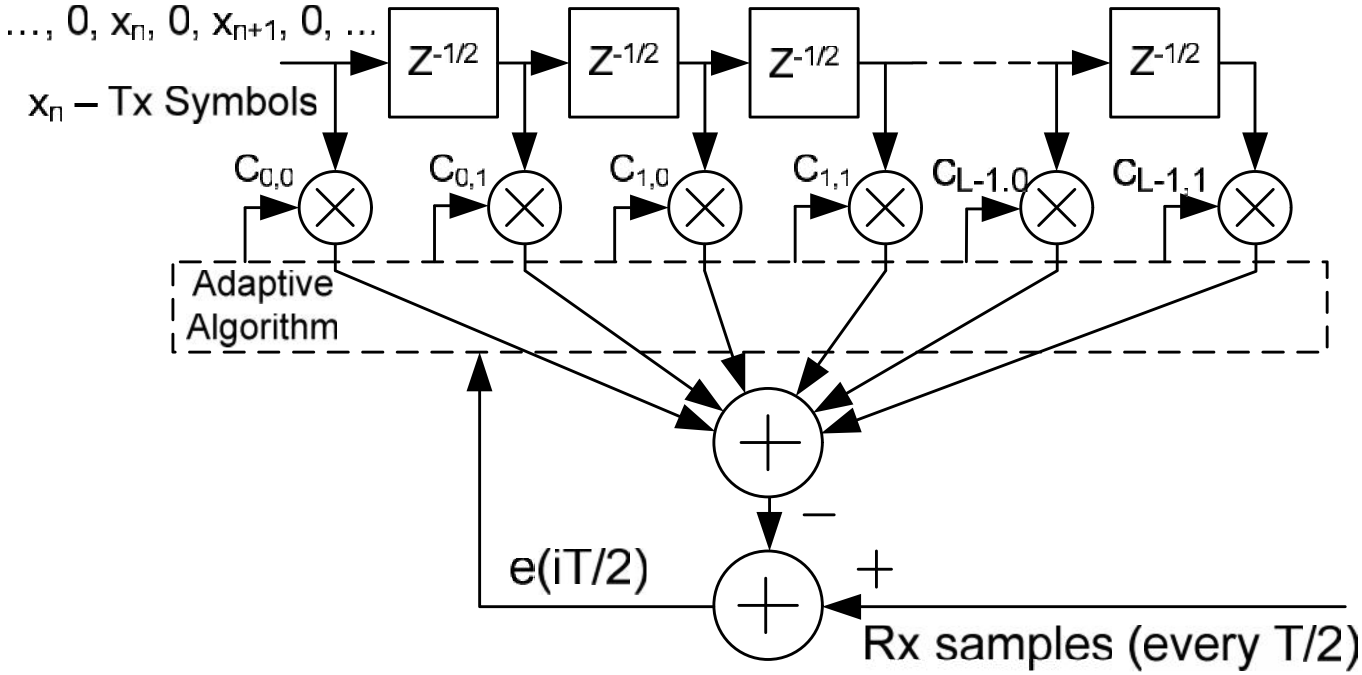
The Basic LMS Nyquist EC/SIC



$$\hat{I}_i(n) = \sum_{k=0}^{L-1} x_{n-k} c_{k,i}(n), \quad e_i(n) = r_i(n) - \hat{I}_i(n)$$

$$c_{k,i}(n+1) = c_{k,i}(n) + \Delta x_{n-k} e_i^*(n), \;\; \Delta \;-\; \text{adaptation step-size}$$

Note: For EC/SIC LMS is as good as LS in general!

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Excess noise in LMS Nyquist EC/SIC

- The coefficients converge towards its optimal value when n goes to infinity.
  - The noise in $r_i(n)$ will introduce errors in the coefficients.
- Analysis of MSE of excess error (also valid for LS)
  - This results in an error term proportional to the irreducible error in $e_i(n)$, called *excess error* denoted by e_{ex}.
  - The MSE of e_{ex} can be expressed as: $£_{ex} = (« / 2) L£$

    $« = \Delta / LE[|x_n|^2]$ – normalized step size, e – MSE of irreducible error, L – the number of coefficients of each sub-canceler
  - For EC/SIC e is the received signal power
    - Residual echo/SI is proportional to the received signal power
    - The residual echo/SI should be 6 dB below the noise level
  - Example: 1. Required SNR g = 27 dB and L = 100, m < 10^{-5}
  - Example: 2: Required SNR g = 21 dB and L = 40, m < 10^{-4}

(These are very small number – very long time constant)

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Tracking Performance of LMS EC/SIC

- Analysis of tracking characteristic of LMS EC/SIC
  - Uncorrelated data symbols – Identity Autocorrelation matrix
    - Uniform exponential convergence for LMS algorithm – identical to exponential LS algorithm
  - The channel estimator can be modeled as a linear system with exponential converging impulse response
    - The input of the system is channel variation
    - Such a system has a impulse response $h(n)=U(n)\mathrm{m}(1\text{-}\mathrm{m})^{n}$, i.e., with a time constant of $(1\text{–}\mathrm{m})^{-1}\mathrm{T}$ and a frequency response:

$$H(e^{j\text{µ}}) = \sum_{n=0}^{\infty} \text{«} e^{-j\text{µ}n}(1-\text{«})^{n} = \frac{\text{«}}{1-e^{-j\text{µ}}(1-\text{«})},\quad \text{«} - \text{LMS step size}$$

  - The ideal estimator has a flat frequency response, i.e., $\mathrm{H}(\mathrm{e}^{j\omega})=1$
  - The estimation error in frequency domain is:

$$1-H(e^{j\text{µ}}) = 1-\frac{\text{«}}{1-e^{-j\text{µ}}(1-\text{«})} = \frac{(1-e^{-j\text{µ}})(1-\text{«})}{1-e^{-j\text{µ}}(1-\text{«})}$$

Cancelation Limit due to Time Variation

- For static channel the estimator is optimal $(1\text{-}H(e^{j\omega}) = 0)$
- For complex sinusoid variation with frequency ω_0:

$$\left|1 - H(e^{j\omega_0})\right|^2 = \frac{4(1-\alpha)^2(1-\cos\omega_0)^2}{(2-\alpha)^2(1-\cos\omega_0)^2 + \alpha^2\sin\omega_0^{\,2}} \approx \frac{(1-\alpha)^2\omega_0^2}{(2-\alpha)^2\omega_0^2/4 + \alpha^2}$$

  - 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 rate is not very fast because
  - High cancellation requirement
  - mis usually very small, e.g., 10^{-3} to 10^{-5}, for small excess MSE at high receiver SNR
- Conclusion: Channel variation will put a limit on achievable cancellation even at very low fading frequency, e.g., 0.05Hz

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IBFD'S ACHIEVABLE PERFORMANCE AND POSSIBLE APPLICATIONS OF

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Achievable Performance of IBFD

- Total achievable cancelation can be summarized by the following empirical formula:

$$R_{c,total} \le \min[(R_{NL} + R_{NL-compensation}), (P_{Total} / P_{ch-\mathrm{var}}) \times R_{ch-\mathrm{var}}] + R_{Isolation}$$

- The first term normally would be in the range of 30-60 dB
  - The non-linearity is usually around –30 dB for higher power amplifiers and may be lower for lower power ones
    - Analog canceller is less impacted by the non-linearity in Tx signal
    - By establish a non-linearity model, the input to the SIC can be pre-distorted and less impacted by the non-linearity
  - There's also non-linearity in the receiver side, which is difficult to compensate
  - The channel variation impacts more on the time-varying path, which yield an interference with lower power
    - It may have less impact to the residual interference

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Achievable Performance of IBFD (cont.)

- Isolation gain depending on the environment and possible antenna arrangement
  - It is essentially achieved by beam forming in a multiple antenna environment
    - Higher gain can be achieved in a base station environment, where multiple transmitter antennas can be deployed
    - It is difficult to achieve isolation gains in a portable device due to close spacing between antennas
  - If there is only a single antenna, circulator is to be used
    - Circulator can only achieve less than 15 dB isolation with reasonable size
    - Using circulator will require higher SIC gain
      - This will be difficult due to the existence of non-linearity?
  - Isolation gain need to be analyzed for specific applications

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Possible Applications of IBFD

- It is difficult to achieve high Self-interference rejection
- High isolation need multiple widely spaced antennas
- It would not be appropriate for applications when the channel attenuation is too high
  - e.g. in large cell mobile communication systems, where link attenuation can be more than 100 dB
- It would be more appropriate for wireless systems with low and/or symmetric link attenuations, such as
  - point to point systems
  - repeaters
  - on base station side of small cell systems
  - In WIFI type of systems

Possible Applications of IBFD (cont.)

- Another possible applications is to use it in a multi-user environment
  - It is a kind similar to multi-user MIMO
  - The base station transmitter is operate in full-duplex mode
    - It transmits to one user device while receives from another user device
  - The user devices can be operated in half-duplex mode or communicating with other devices (full-duplex)

- *To determine the appropriate applications of IBFC, the most important factor is to determine the possible isolation/cancellation gain vs. the worst case self-interference to received signal ratio*

TOPICS OF FUTURE RESEARCH AND FINAL REMARKS

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Possible Research Topics

- Physical Layer:
  - The environmental study of various potential systems
    - For any potential candidate of using IBFD, it is necessary to achieve best possible signal isolation
    - It is necessary to investigate the operating environment by characterization of self-interference channels
      - Direct and reflective channel characteristics
      - Fading characteristic of the channels
  - Validation of the tracking performance of adaptive algorithms in fading environment
    - The given derivation is based on the linear system model
    - While it is reasonable assumption, further validation is needed
    - It will be desirable to also verify using real (measured) system model

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Possible Research Topics (cont.)

- Physical Layer (cont.)
  - The compensation techniques for non-linearities
    - Model the non-linearity of practical RF amplifiers
    - Utilize the model to pre-distorted Tx symbols before enter the SIC canceller
      - It is theoretically possible but no reported result to show what has been and or can be done
  - Impact of phase-noise and its compensation
    - Techniques of reducing phase noise in RF amplifier/components
    - Compensation techniques
  - Analog canceller implementation and adaptation algorithms
    - Reduction of the impact of non-linearity: what is the achievable performance?
    - What is the best practical way to implement analog canceller?
- System topology and upper layer study of IBFD
  - I would let others to propose ☺

Concluding Remarks

- IBFD have the potential to double spectrum efficiency for certain applications under appropriate environments
- So far it has been demonstrated for limited circumstances
  – Mainly point-to-point system such as repeaters and backhaul connections
- It is important to determine such applications that can utilize this technology
- Effort should be made to analyze the achievable self interference reduction under different environments
- Experience obtained from echo cancellation in past decades can provide useful information and guideance for development of IBFD systems

Concluding Remarks (cont.)

- For being useful in practical applications, we need to consider the worst case
  - Robustness is more important than best achievable performance
- Cost factors need to be considered for its applicability
  - There's many different ways to improve spectrum efficiency

- *Total achievable cancellation is usually less than the sum of the individually achievable cancelations of the blocks*
- *It is not a miracle formula of doubling capacity of any existing applications*

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THANK YOU!

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