In-band Full Duplex Radios and System Performance

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Outline

- **Feasibility of In-band Full Duplex (IFD)**
  - Concept
  - Merit
  - Demerit
  - Classification of self-interference cancellation (SIC) Technology
  - State of the art in SIC
- **System Performance**
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  - Duplex mode
    - **TDD vs. 3-node form IFD**
    - **TDD vs. Pairwise IFD**
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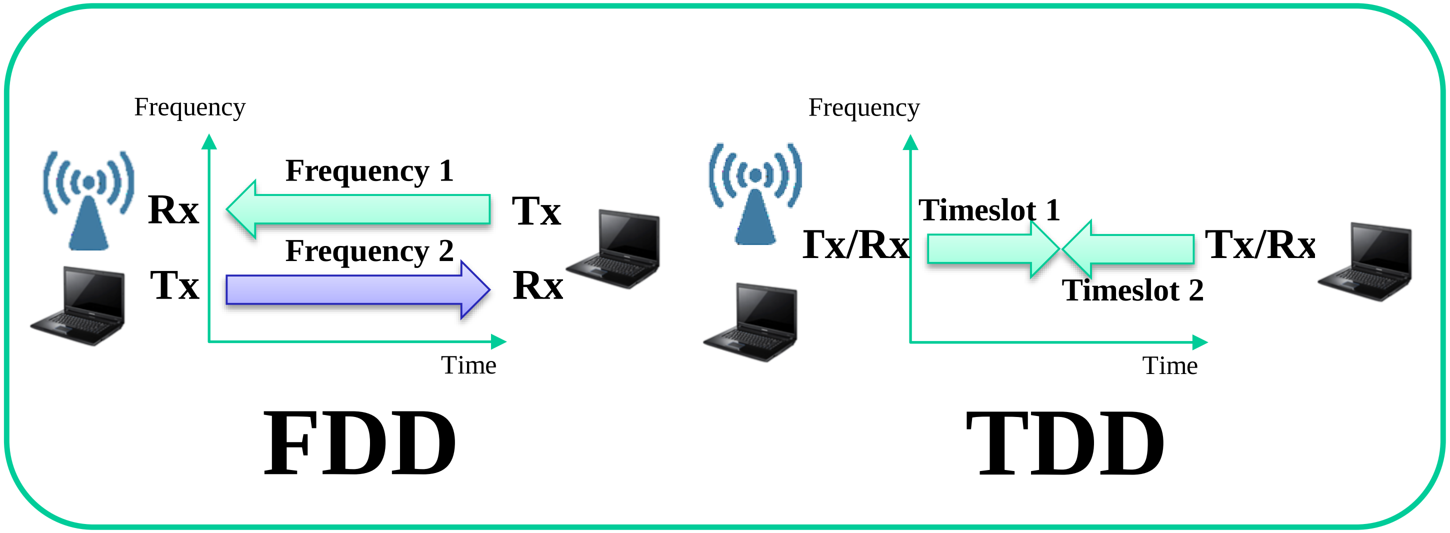
    - **Evaluation result**
  - Outdoor large BSS scenario
    - **System-level simulation environment**
    - **Evaluation result**
- **Summary**

Feasibility of In-band Full Duplex (IFD)

What are current wireless radios?

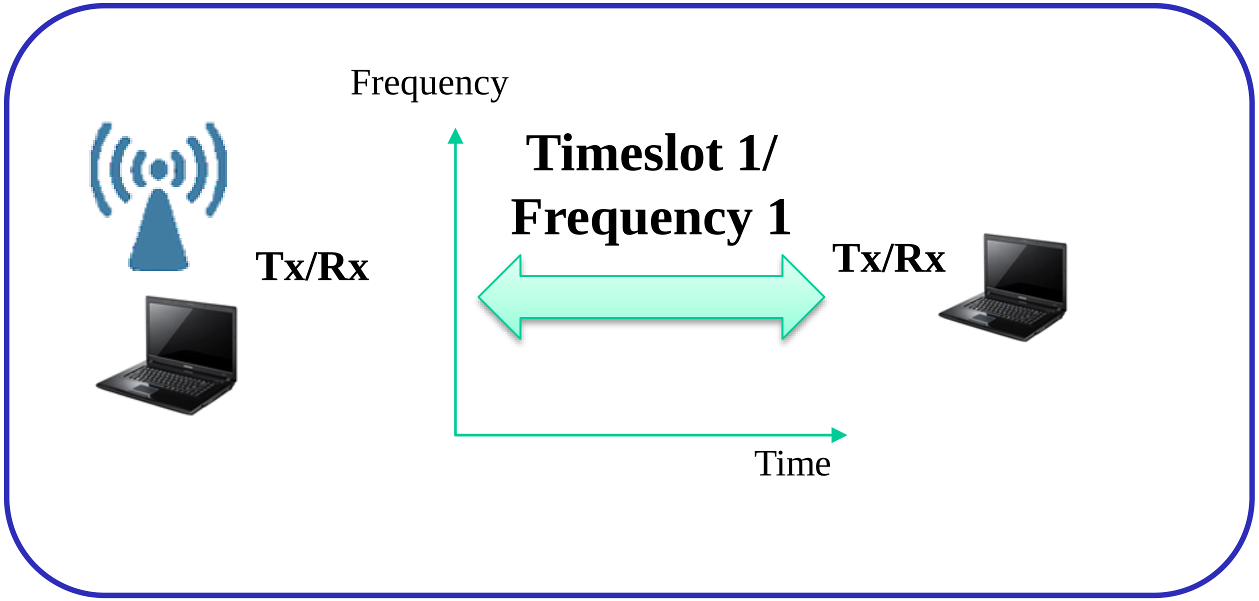
- **Frequency Division Duplexing (FDD)**
  - In other words, Out-band Full Duplex (OFD)
- **Time Division Duplexing (TDD)**
  - In other words, In-band Half Duplex (IHD)



- **Problem**
  - There is no full resource utilization.
    - **FDD wastes frequency resource, i.e. Frequency 2.**
    - **TDD wastes time resource, i.e. Timeslot 2.**
- **What is one of solutions to resolve the problem?**
  - That is "In-band Full Duplex (IFD)".

Concept of IFD

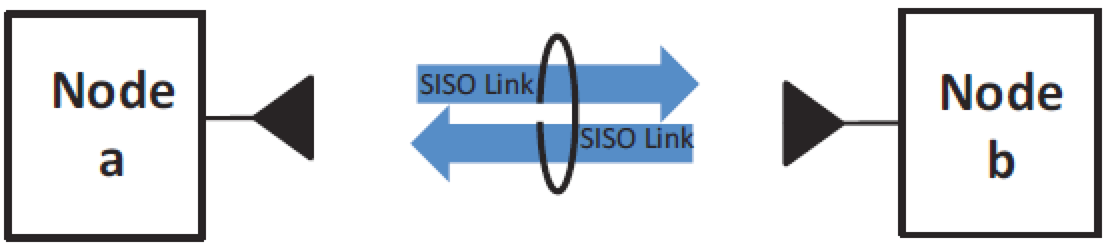
- ❖ **IFD radio can simultaneously transmit and receive on the same frequency channel**



- IFD does not waste frequency and time resources, i.e. Frequency 2 and Timeslot 2.

Merit: Spectral Efficiency

❖ **Basic operating scenario of bi-directional IFD communications with single antenna**

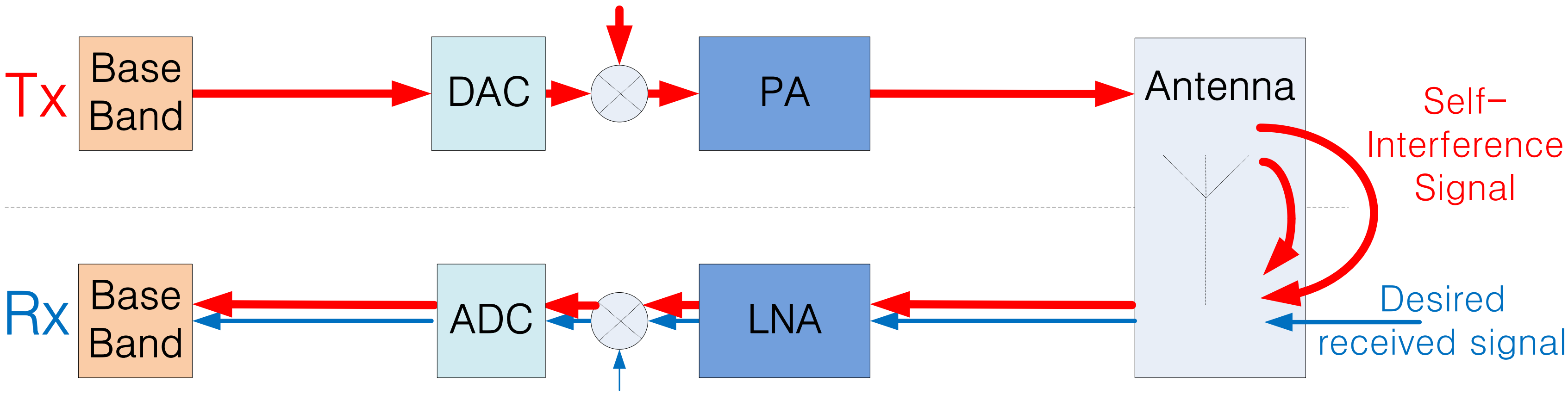


- Theoretical Ergodic capacities of ideal IFD and OFD/IHD
  - $C_{IFD} = 1 \times C_{ab}^{(1\times1)} + 1 \times C_{ba}^{(1\times1)}$
  - $C_{OFD/\mathrm{IHD}} = \frac{1}{2} \times C_{ab}^{(1\times1)} + \frac{1}{2} \times C_{ba}^{(1\times1)}$, where $C_{xy}^{(1\times1)} = \log_2\left(1 + SNR_{xy}^{(1\times1)}\right)$
  - **The link capacity of IFD is double than that of OFD/IHD.**

Demerit: Self-Interference

❖ Basic transceiver structure

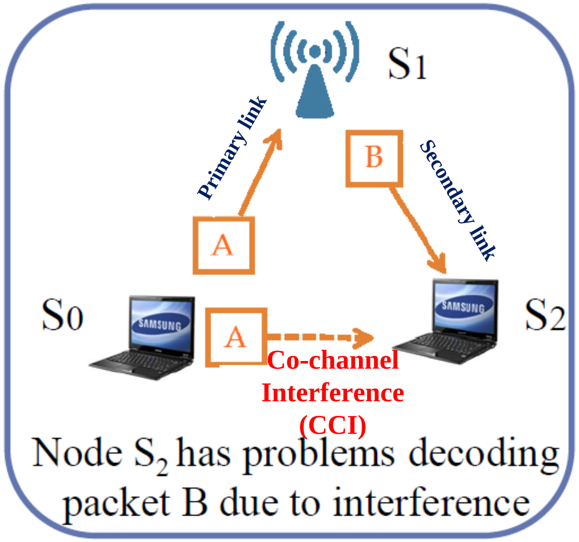
- Self-interference (i.e. self transmitted signal) is generated as below.



- Very strong self-interference signal [1]
  - **~110dB stronger than desired received signal strength for IEEE 802.11 Wi-Fi and LTE-A Small Cell**

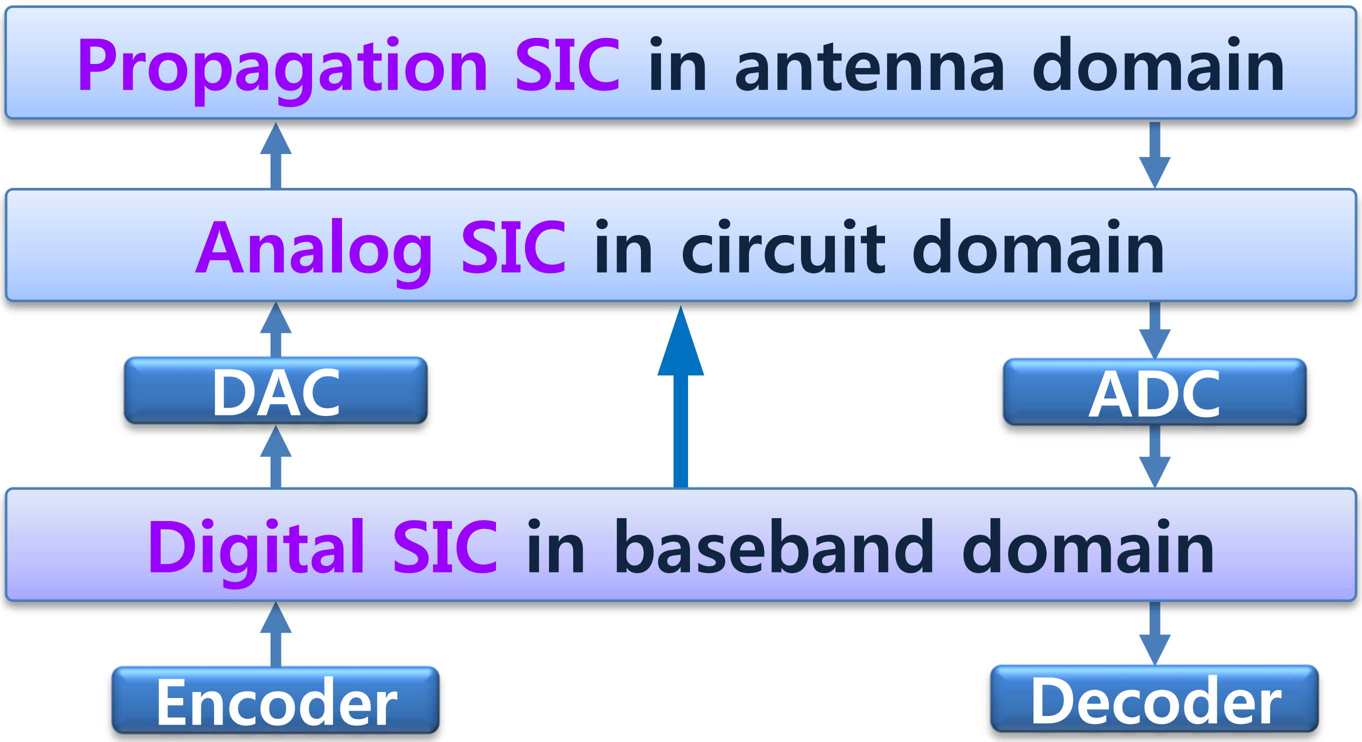
Demerit: Co-Channel Interference

- **Operating scenario of IFD capable AP supporting IHD capable user nodes [2],[3]**
  - It can be a priority for AP only to have IFD capability in terms of power supplying and backward compatibility.



  - Co-channel interference (CCI) occurs.
  - Requires further information (e.g. CCI) to setup the secondary link

Classification of SIC Technology



Inefficiency of propagation SIC (PSIC)

- Mainly using physical isolation between Tx and Rx antennas [4]
  - **Any propagation SIC technologies are not recommended because**
    - the merit of IFD in terms of spectral efficiency over OFD/IHD disappears
    - The form-factor size of IFD transceiver becomes larger.
  - **Thus, single antenna is recommended to realize the merit of spectral efficiency**
    - That is to say, no propagation SIC gain in antenna domain

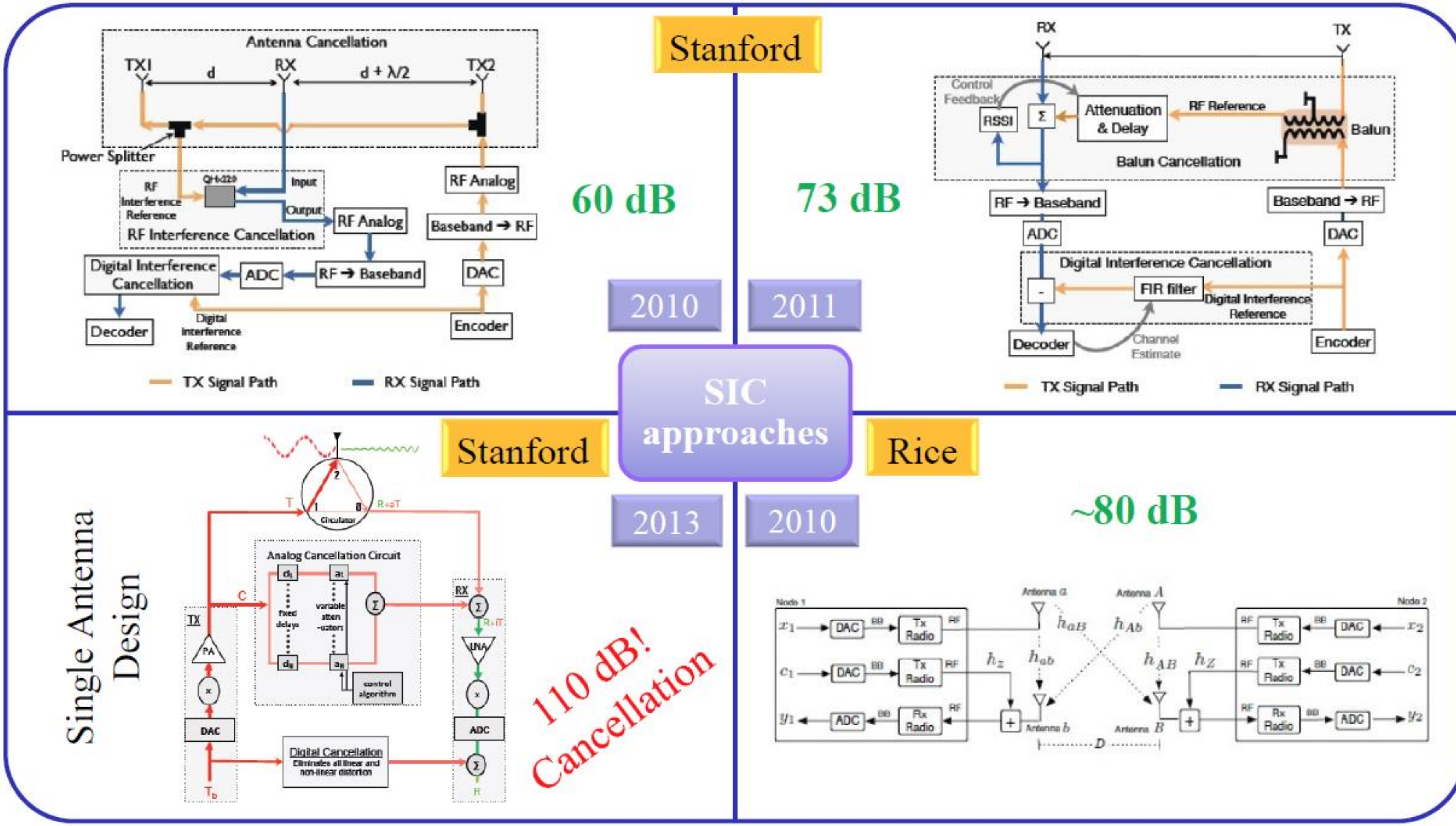
Importance of analog SIC (ASIC)

- Protecting analog-to-digital converter (ADC) saturation
- Analog SIC technology is the crux of IFD commercialization.

Non-linear component in digital SIC (DSIC)

- Dependent on surrounding environment of IFD transceiver, non-linear component self-interference signal cannot be sufficiently cancelled in analog domain. In this case, there is no successful decoding without this component cancellation.

State of the art in SIC [2]

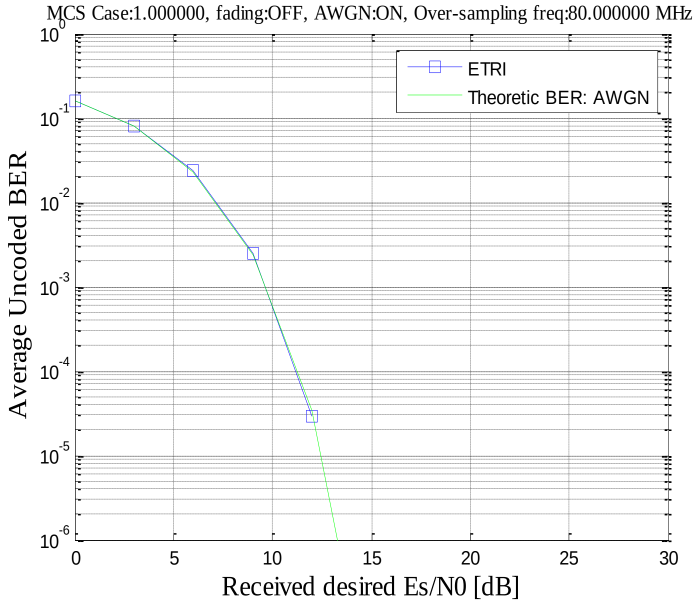


State-of-the-art SIC Performance Comparison

<table>
<tr><th>Institute</th><th>Year (Standard)</th><th>Freq. (GHz)</th><th>BW (MHz)</th><th>PSIC</th><th>ASIC</th><th>DSIC</th><th>Total SIC</th></tr>
<tr><td>NEC (Japan)</td><td>2011</td><td>5</td><td>10</td><td>55dB</td><td>none</td><td>20dB</td><td>75dB</td></tr>
<tr><td rowspan="3">Rice University (US)</td><td>2011</td><td>2.4</td><td>10</td><td>57dB</td><td>24dB</td><td>none</td><td>81dB</td></tr>
<tr><td>2012</td><td>2.4</td><td>20</td><td>65dB</td><td colspan="2">20dB</td><td>85dB</td></tr>
<tr><td>2012</td><td>2.4</td><td>20</td><td>71dB</td><td colspan="2">24dB</td><td>95dB</td></tr>
<tr><td rowspan="3">Stanford University Kumu networks [1] (US)</td><td>2010</td><td>2.48</td><td>5</td><td>30dB</td><td>25dB</td><td>15dB</td><td>70dB</td></tr>
<tr><td>2011</td><td>2.4</td><td>10</td><td></td><td>45dB</td><td>28dB</td><td>73dB</td></tr>
<tr><td>2013</td><td>2.4</td><td>80</td><td>none</td><td>60dB</td><td>50dB</td><td>110dB</td></tr>
<tr><td>DUPLO [6]</td><td>2014</td><td>2.45</td><td>6</td><td>none</td><td>50dB</td><td></td><td></td></tr>
<tr><td>RF Window (Korea)</td><td>LTE WCDMA</td><td>2</td><td>20</td><td>60dB</td><td>none</td><td>10dB</td><td>70dB</td></tr>
<tr><td>WITHUS (Korea)</td><td>LTE WCDMA</td><td>2</td><td>10</td><td>35dB</td><td>none</td><td>35dB</td><td>70dB</td></tr>
<tr><td>AirPoint (Korea)</td><td>LTE TDD</td><td>2.2</td><td></td><td>55dB</td><td>none</td><td>35dB</td><td>90dB</td></tr>
<tr><td>SOLiD (Korea)</td><td></td><td>2</td><td></td><td>65dB</td><td>none</td><td>35dB</td><td>100dB</td></tr>
</table>

ETRI View and Result on SIC

- **Propagation SIC**
  - No need to achieve double spectral efficiency, that is, single shared antenna
- **Analog SIC**
  - Supporting wide bandwidth e.g. 100MHz
  - Achieving at least **stable** 80dB SIC to reduce quantization error in digital domain
    - **RF analog FIR filter is needed**
- **Digital SIC**
  - Designing residual nonlinear component SIC as well as linear-component SIC for successful decoding
- **Result based on S/W simulator**
  - Condition (refer to the right figure)
    - **Single antenna, Circulator/Antenna channel modelling, Low Pass Filter modelling, nonlinear amplifier modelling**
    - **No consideration in other hardware impairments**
  - We see more than 110dB SIC with our SIC technologies.



System Performance and Summary

Introduction

- **IFD with single antenna is coming**
  - Feasibility of IFD communication now proved [1]
  - ***Dream of simultaneous transmission and reception (STR) coming true!!***

- **When IFD is employed in wireless communication networks,**

- **Up to 2x spectral efficiency**
- **Advanced MAC protocols to resolve various problems in half duplex (HD) counterparts**

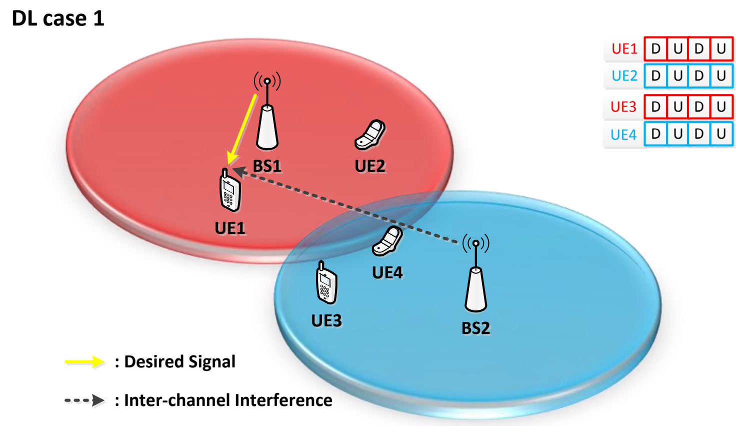
VS.

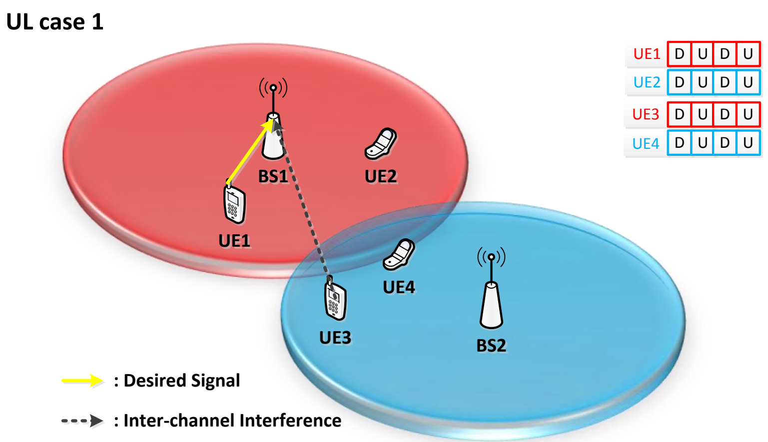
- **Self-Interference**
- **Increased co-channel interference (CCI) by STR**

- **Performance IFD-based wireless communication networks by system level simulation (SLS)**

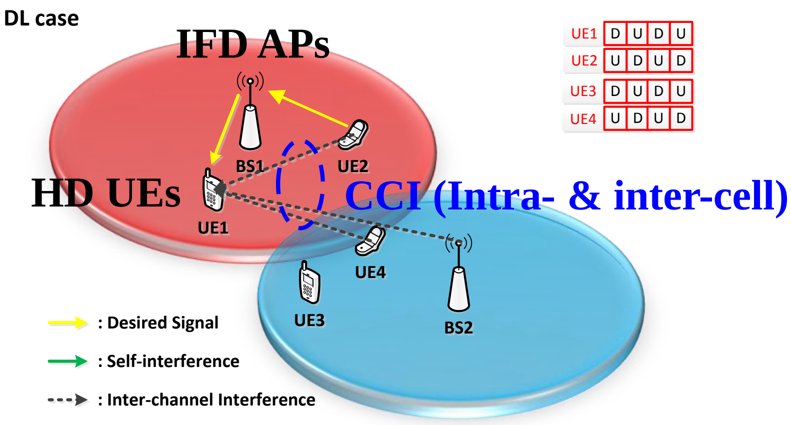
Duplex Mode – TDD vs. 3 Node IFD

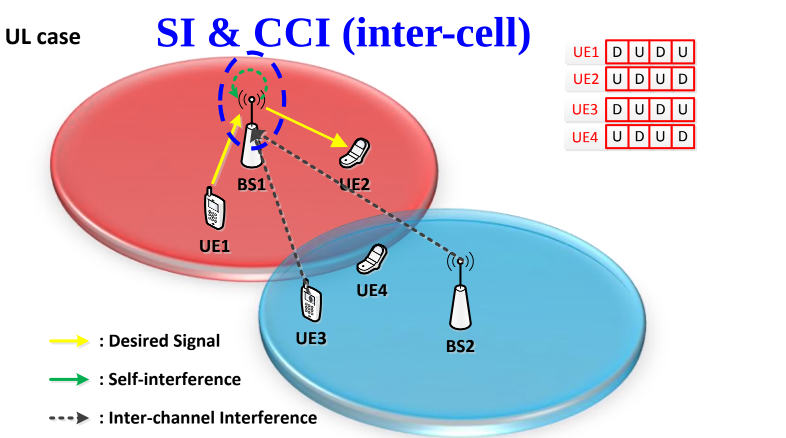
TDD





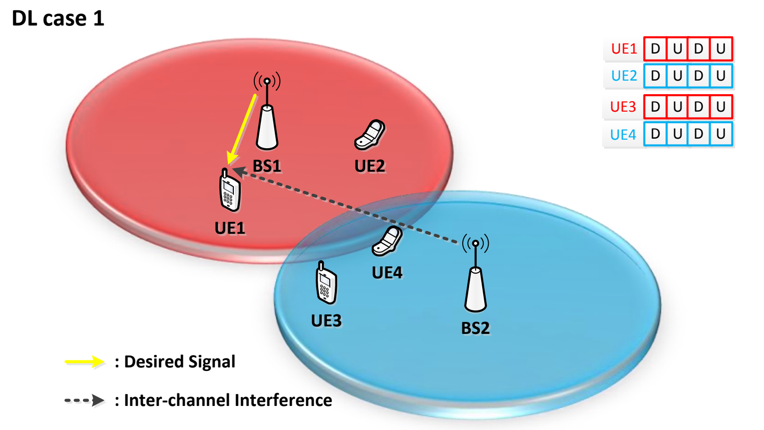
3 Node Form IFD (3n-IFD) [2][3]

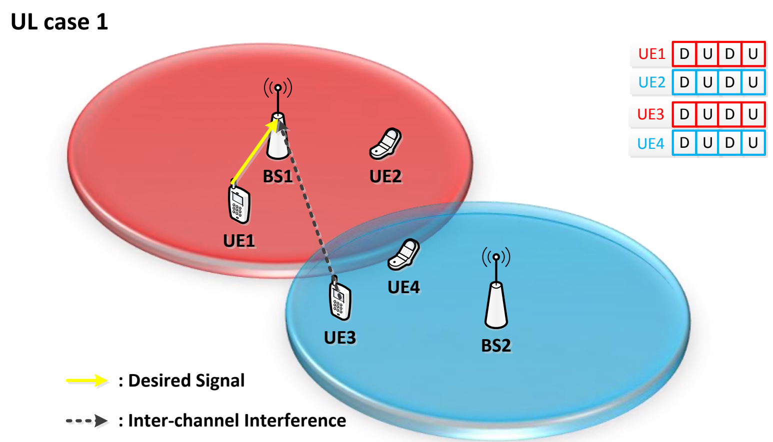




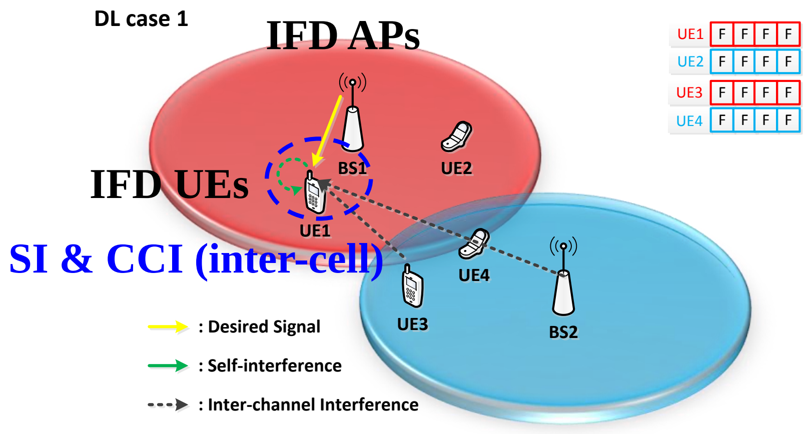
Duplex Mode – TDD vs. Pairwise IFD

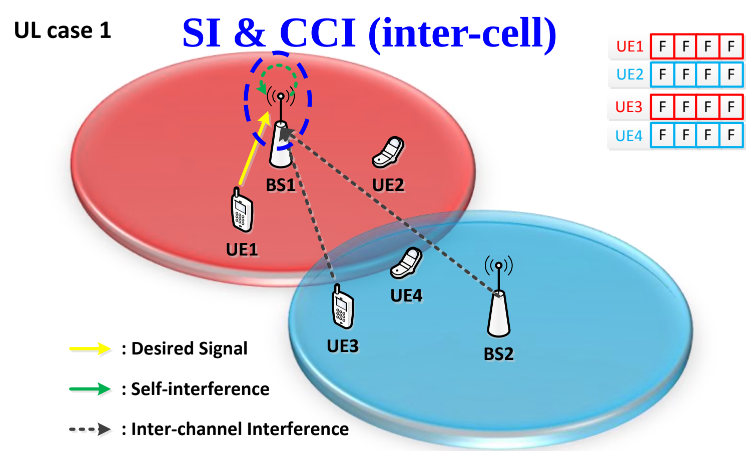
TDD





Pairwise IFD (P-IFD) [2][3]

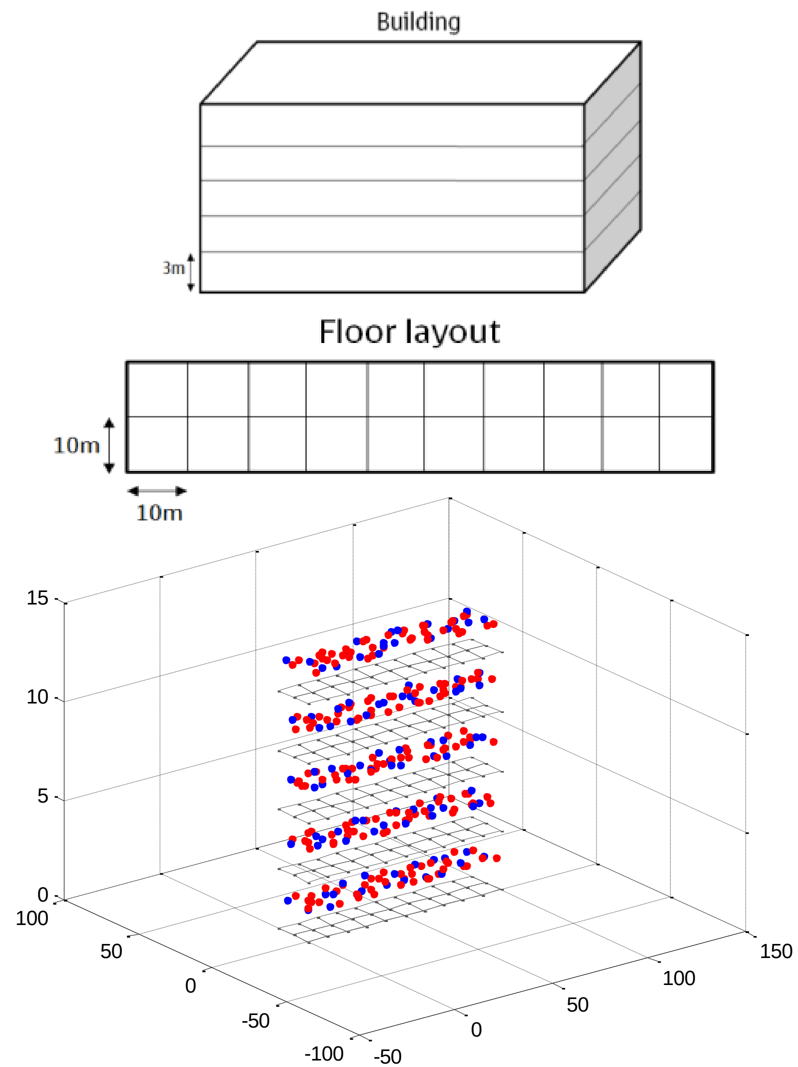




Residential Scenario

❖ SLS Environment [5]

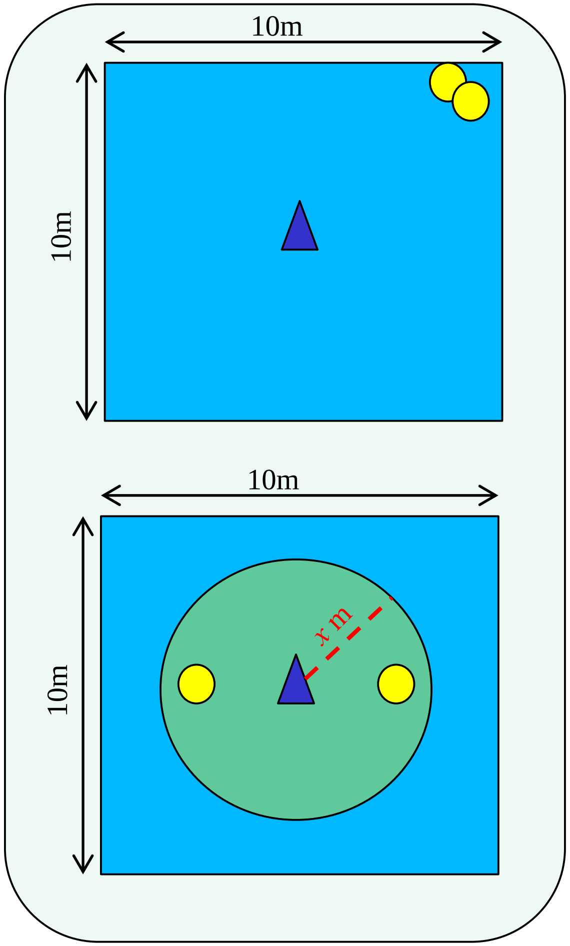
- Residential building layout
  - 5 floors, 3m height / floor
  - 2×10 apartments / floor
  - Apartment size : 10m×10m×3m
- Parameter
  - 100 APs in the building (1 AP / room)
  - 2 STAs / room
  - Carrier frequency : 2.4GHz
  - Bandwidth : 20MHz
  - Noise Figure : 7dB
  - TDD mode
    - AP: 2 Tx and 2 Rx antennas
    - STA: 1 Tx and 1 Rx antennas
  - IFD mode
    - AP: 2 shared antennas
    - STA: 1 shared antenna



Residential Scenario

❖ SLS Environment (Contd.)

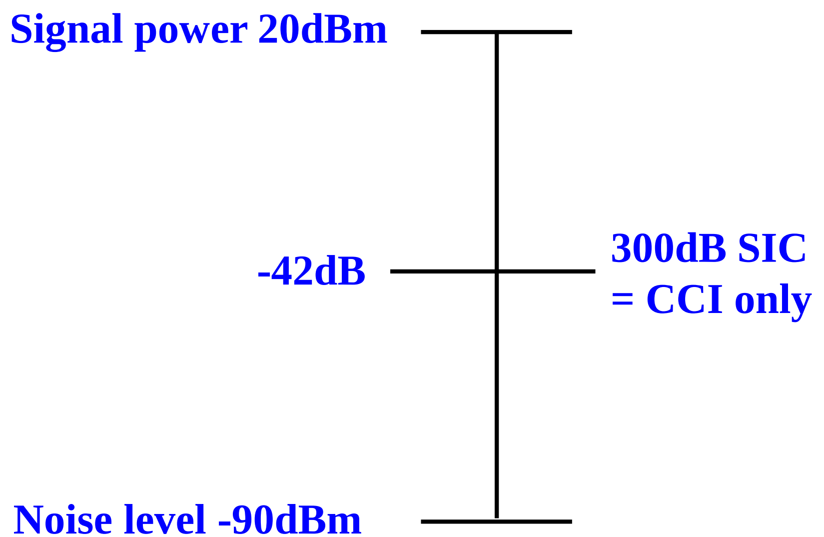
- General P-IFD case
  - ➢ **AP : random deployment in room (uniform)**
  - ➢ **STA : random deployment in room (uniform)**
- Space-Scheduled (SSC) P-IFD & 3n-IFD
  - ➢ **AP : random deployment in room (uniform)**
  - ➢ **STA**
    - Random deployment (uniform)
      - **minimum distance between STAs is 2m**
      - **minimum distance between AP and STA is *x* m**

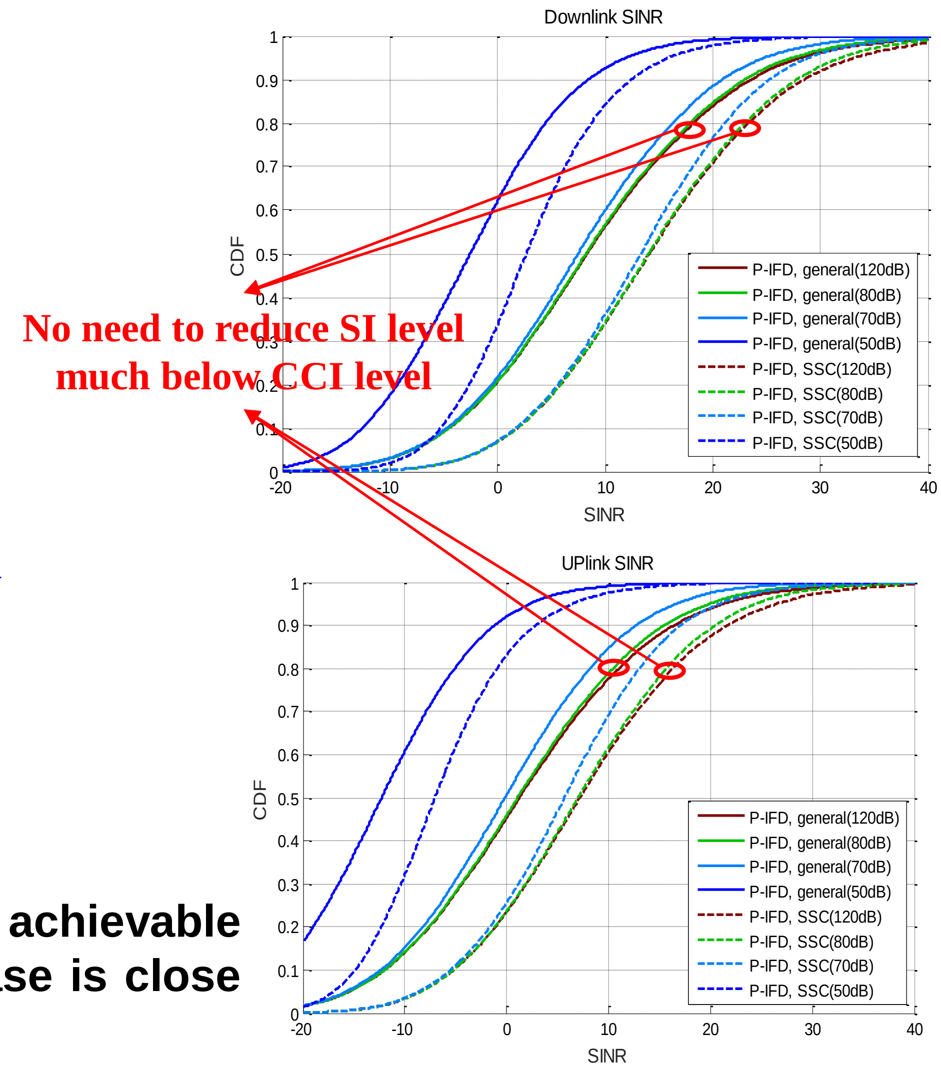


Residential Scenario

❖ Evaluation Result (1)

- Effect of CCI



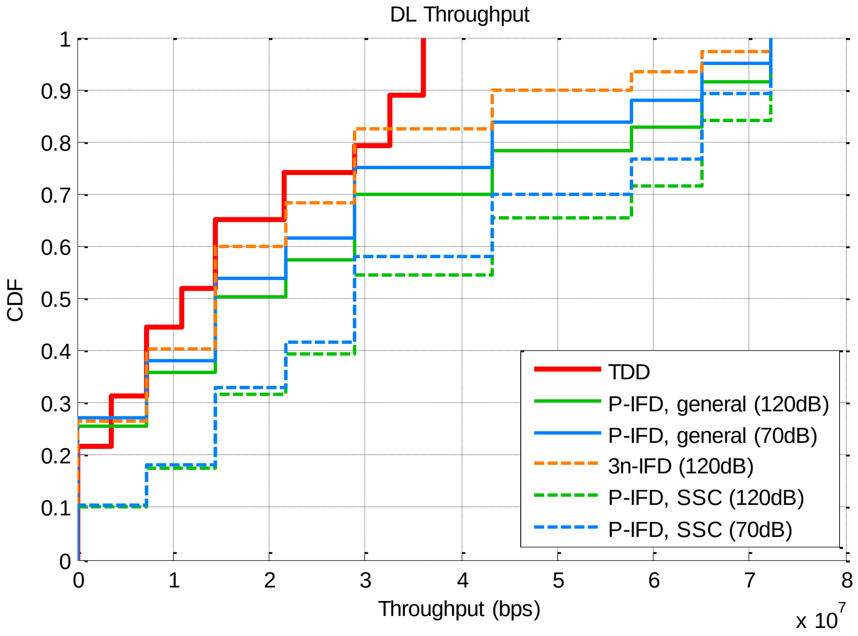


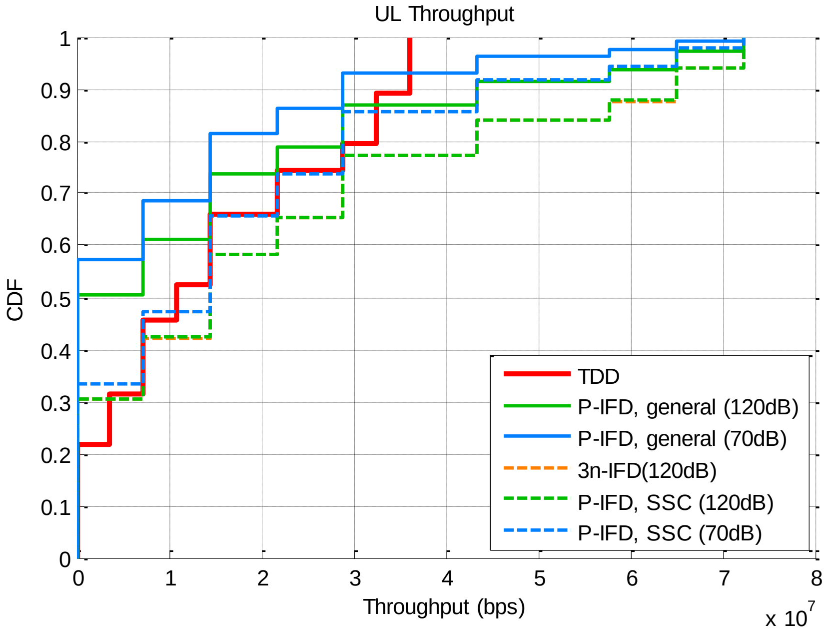
➢ **It means in this CCI level, the achievable throughput with 80-dB SIC case is close to that with perfect SIC case.**

Residential Scenario

❖ Evaluation Result (2)

- Throughput



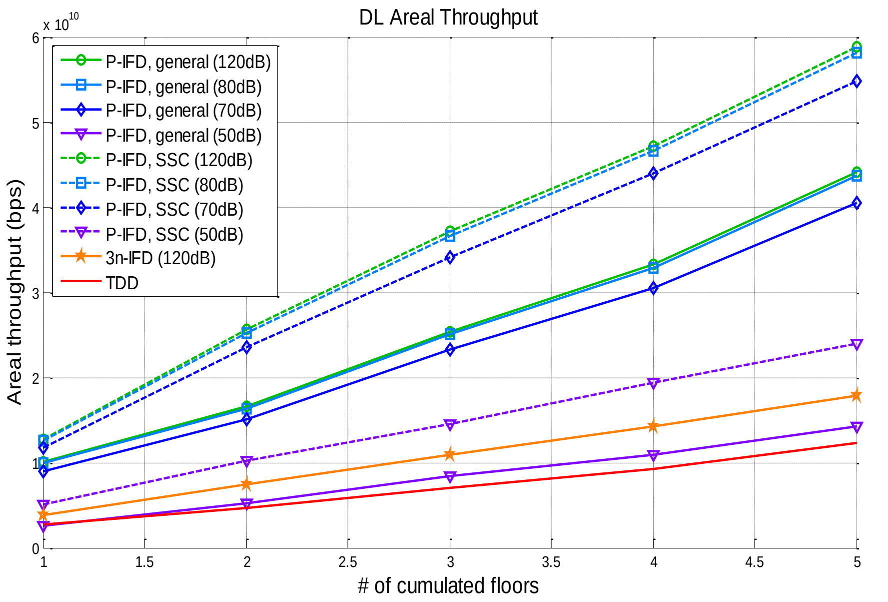


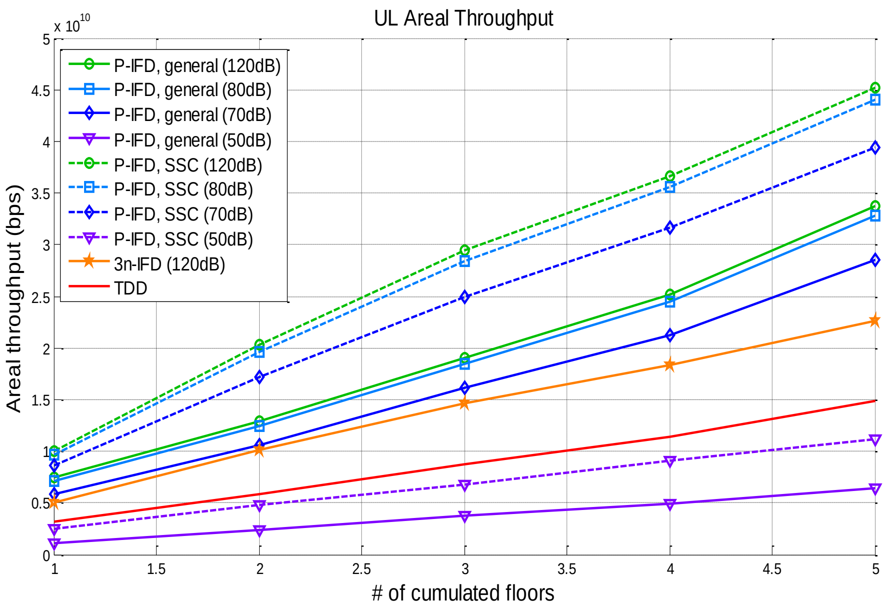
- **Max. throughput of IFD ≈ 2 x max. throughput of TDD.**
- **SSC is effective to enhance throughput of IFD.**

Residential Scenario

❖ Evaluation Result (3)

- Areal Throughput



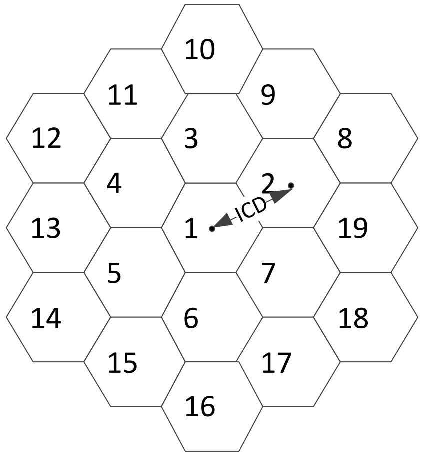


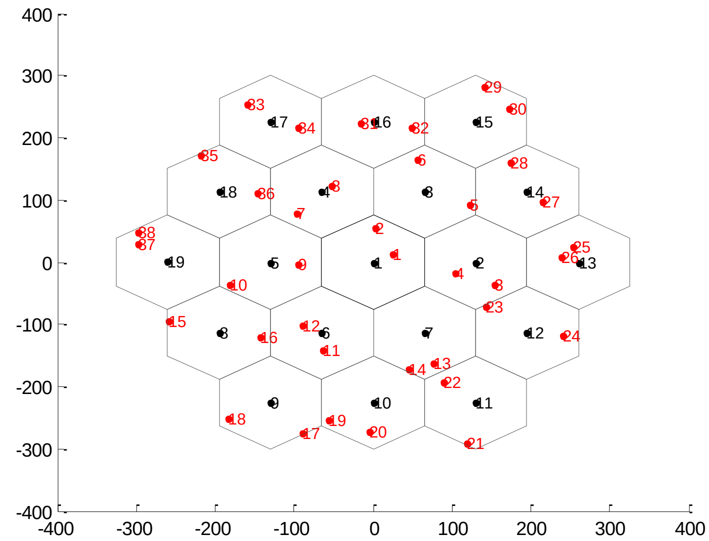
- **50% enhancement of areal throughput by 3n-IFD with sufficient SIC**
- **300% enhancement of areal throughput by P-IFD with sufficient SIC**
- **Minimum SIC requirement for P-IFD : 50dB for STA, 70dB for AP**
- **Noticeable areal throughput enhancement by SSC**

Outdoor Large BSS Scenario

❖ SLS Environment [5]

- BSSs' layout
  - ➢ **19 hexagonal grids of cells**
  - ➢ **Inter cell distance (ICD) = 130m**
- Location
  - ➢ **1 AP at the center of each cell**
  - ➢ **2 randomly distributed STAs / cell**
  - ➢ **Heights: h_{AP}=10m, h_{STA}=1.5m**
- Parameter
  - ➢ **Carrier Frequency : 2.4GHz**
  - ➢ **Bandwidth : 20MHz**
  - ➢ **Noise Figure : 7dB**
  - ➢ **TDD mode**
    - ▪ AP: 2 Tx and 2 Rx antennas
    - ▪ STA: 1 Tx and 1 Rx antennas
  - ➢ **IFD mode**
    - ▪ AP: 2 shared antennas
    - ▪ STA: 1 shared antenna

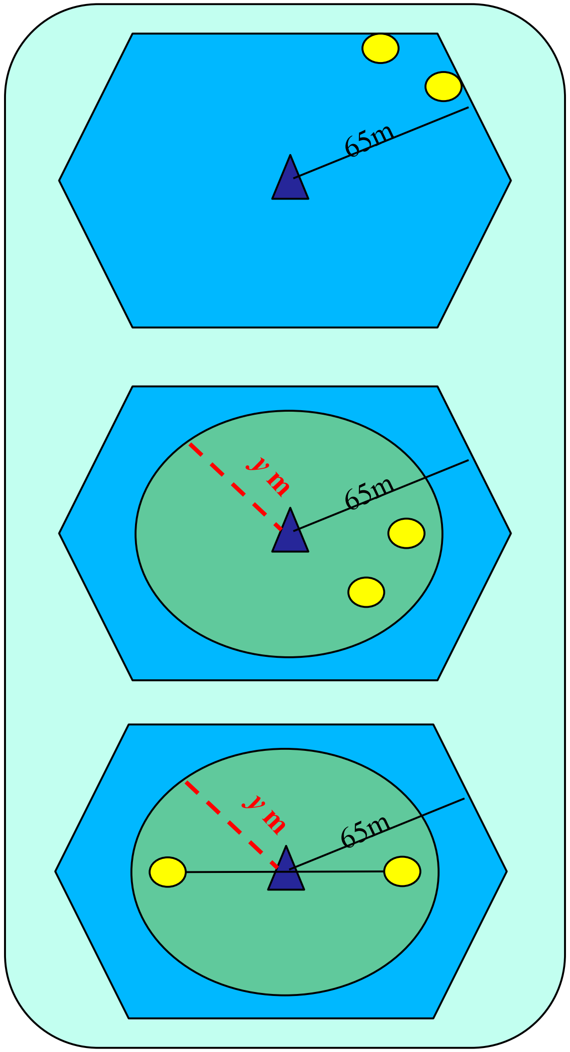




Outdoor Large BSS Scenario

❖ SLS Environment (Contd.)

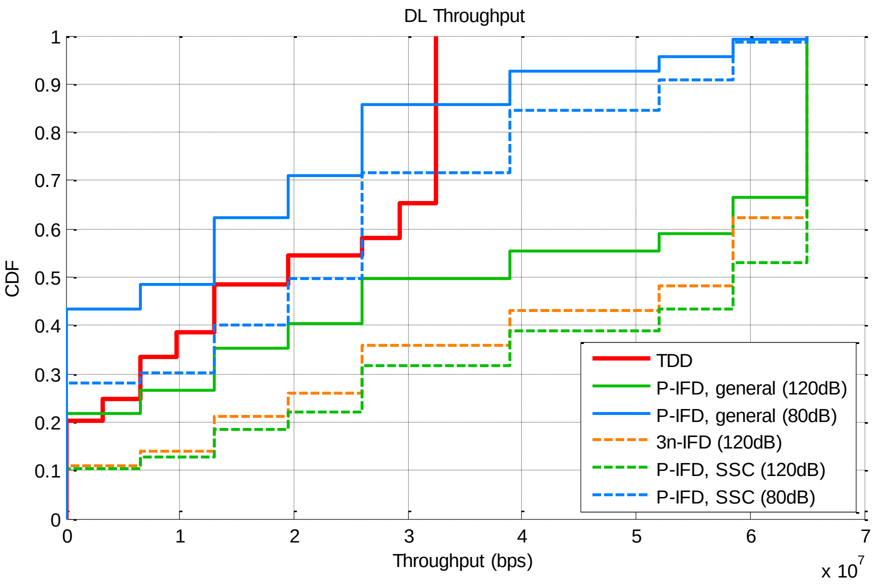
- General P-IFD
  - **Random deployment (uniform)**
  - **Minimum distance b/w AP & STA : 10m**
  - **Minimum distance b/w STAs : 10m**
- SSC P-IFD
  - **Random deployment (uniform)**
  - **Distance b/w AP & STA: 10 m ~ *y* m**
  - **Minimum distance b/w STAs : 10m**
- SSC 3n-IFD
  - **Random deployment (uniform)**
  - **Odd STA : random deployment within boundary**
  - **Even STA : reflection of odd STA**
  - **Distance b/w AP & STA: 10 m ~ *y* m**

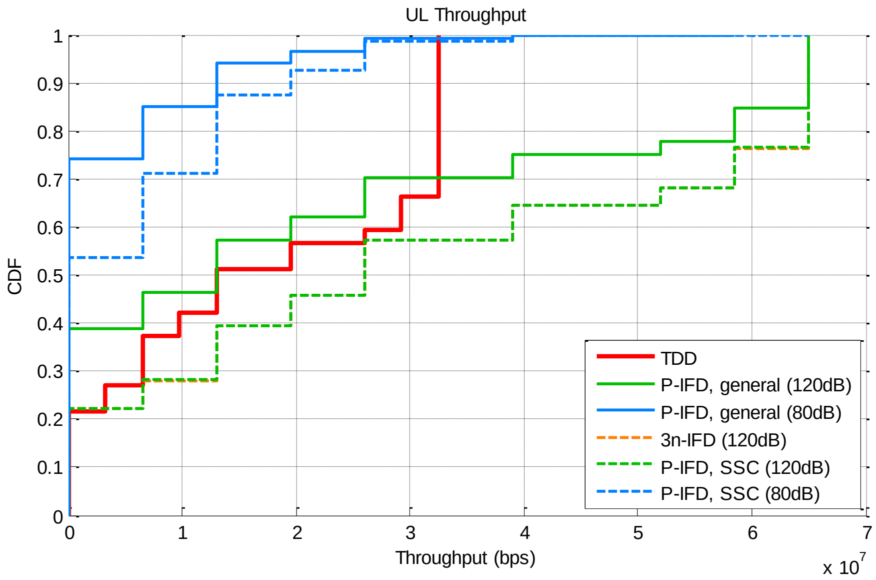


Outdoor Large BSS Scenario

❖ Evaluation Result (1)

- Throughput



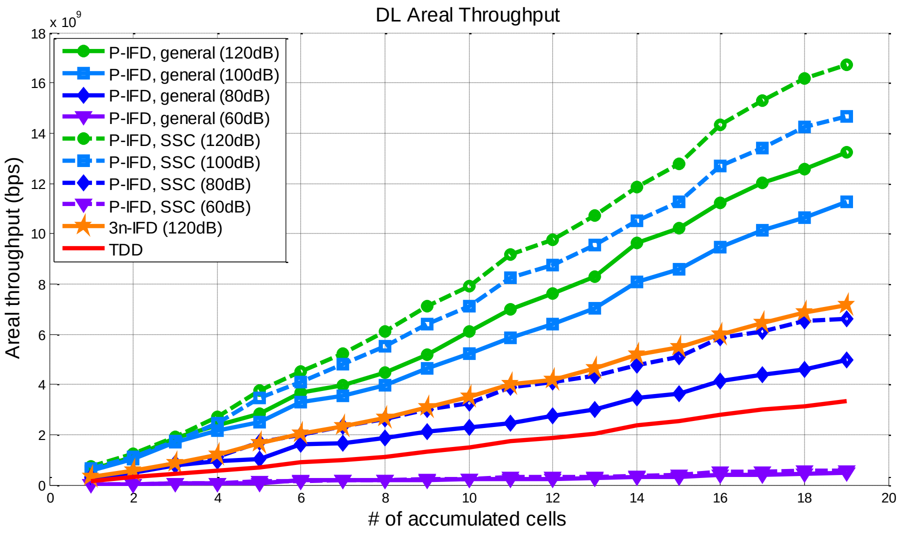


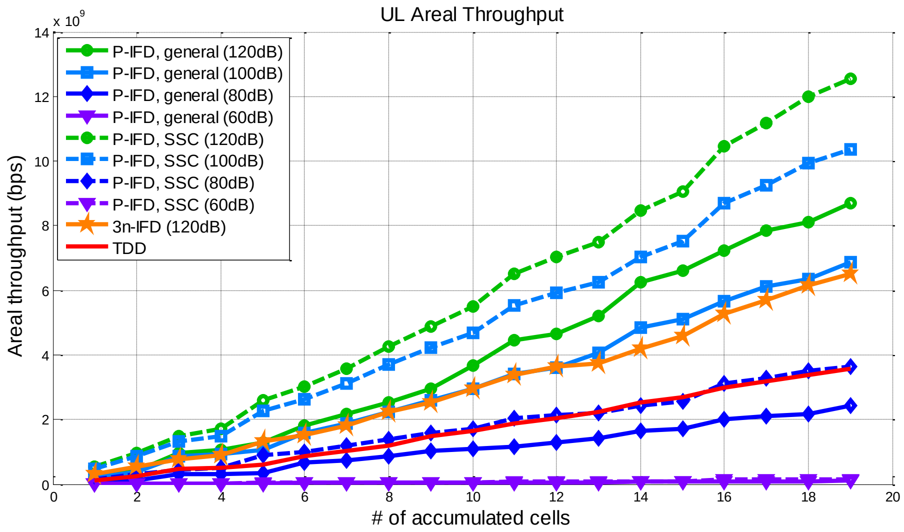
- **Max. throughput of IFD ≈ 2 x max. throughput of TDD.**
- **SSC is effective to enhance throughput of IFD in low SINR regime**
- **Even with SSC, SIC more than 80dB required**

Outdoor Large BSS Scenario

❖ Evaluation Result (2)

- Areal throughput





- **100% areal throughput enhancement by 3n-IFD with sufficient SIC**
- **300% areal throughput enhancement by P-IFD with sufficient SIC**
- **Minimum SIC requirement for P-IFD : 80dB for STA, 100dB for AP**
- **Noticeable areal throughput enhancement by SSC**

Summary

- Simultaneous transmission and reception is coming.
- When deployed in Wi-Fi networks, the system throughput with 80dB SIC case approached that with perfect SIC case (indoors).
- When STA density is low, extra SIC performance can further enhance the system throughput (outdoors).
- System level simulations show that with sufficient SIC performance, IFD leads to severalfold throughput enhancements compared to conventional half duplex counterpart.
- (Spatial) scheduling plays a key role to enhance performance of IFD-based Wi-Fi networks.

References

1. IEEE 802.11-13/1421r1, “STR radios and STR media access.”
2. IEEE 802.11-13/1122r1, “Considerations for In-Band Simultaneous Transmit and Receive (STR) Feature in Hew”
3. IEEE 802.11-14/0838r0, “Discussion on Dual-Link STR in IEEE 802.11 ax”
4. E. Everett, A. Sahai, and A. Sabharwal, “Passive self-interference suppression for full-duplex infrastructure nodes,” IEEE Trans. Wireless Commun., vol. 13, no. 2, pp. 680-694, Feb. 2014.
5. IEEE 802.11-14/0980r4, “TGax Simulation Scenarios.”
6. DUPLO, ‘D4.1.1-Performance of full-duplex systems,’ http://www.fp7-duplo.eu/index.php/.

Appendix

MCS table

❖ Using IEEE 802.11n

- Spatial streams = 1
- Bandwidth = 20MHz
- Residential Scenario 400ns GI
- Outdoor Large BSS Scenario 800ns GI

MCS index	Modulation type	Coding rate	Data rate (Mbits/s) 20MHz channel 800ns GI	400ns GI
0	BPSK	1/2	6.5	7.2
1	QPSK	1/2	13	14.4
2	QPSK	3/4	19.5	21.7
3	16-QAM	1/2	26	28.9
4	16-QAM	3/4	39	43.3
5	64-QAM	2/3	52	57.8
6	64-QAM	3/4	58.5	65
7	64-QAM	5/6	65	72.2

MCS Value Achieved by Clients at Various Signal to Noise Ratio Levels (SNR)

Protocol	Channel	1	2	3	4	5	6	7	8	9	10
802.11b	20MHz	None	None	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1	MCS 1
802.11a/g	20MHz	None	MCS 0	MCS 0	MCS 1	MCS 2	MCS 2	MCS 2	MCS 2	MCS 3	MCS 3
802.11n	20MHz	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1	MCS 1	MCS 2	MCS 2
802.11n	40MHz	None	None	None	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1
802.11ac	20MHz	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1	MCS 1	MCS 2	MCS 2
802.11ac	40MHz	None	None	None	None	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1
802.11ac	80MHz	None	None	None	None	None	None	None	MCS 0	MCS 0	MCS 0
802.11ac	160MHz	None	None	None	None	None	None	None	None	None	None

	SNR in dB	11	12	13	14	15	16	17	18	19	20
802.11b	20MHz	MCS 2	MCS 2	MCS 2	MCS 2	MCS 2	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3
802.11a/g	20MHz	MCS 4	MCS 4	MCS 4	MCS 4	MCS 5	MCS 5	MCS 5	MCS 6	MCS 6	MCS 7
802.11n	20MHz	MCS 3	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4	MCS 5	MCS 5	MCS 6
802.11n	40MHz	MCS 1	MCS 2	MCS 2	MCS 3	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4
802.11ac	20MHz	MCS 3	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4	MCS 5	MCS 5	MCS 6
802.11ac	40MHz	MCS 1	MCS 2	MCS 2	MCS 3	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4
802.11ac	80MHz	MCS 1	MCS 1	MCS 1	MCS 1	MCS 2	MCS 2	MCS 3	MCS 3	MCS 3	MCS 3
802.11ac	160MHz	MCS 0	MCS 0	MCS 0	MCS 1	MCS 1	MCS 1	MCS 1	MCS 2	MCS 2	MCS 3

	SNR in dB	21	22	23	24	25	26	27	28	29	30
802.11b	20MHz	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3
802.11a/g	20MHz	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7
802.11n	20MHz	MCS 6	MCS 6	MCS 6	MCS 6	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7
802.11n	40MHz	MCS 5	MCS 5	MCS 6	MCS 6	MCS 6	MCS 6	MCS 6	MCS 7	MCS 7	MCS 7
802.11ac	20MHz	MCS 6	MCS 6	MCS 6	MCS 6	MCS 7	MCS 7	MCS 7	MCS 7	MCS 8	MCS 8
802.11ac	40MHz	MCS 5	MCS 5	MCS 6	MCS 6	MCS 6	MCS 6	MCS 6	MCS 7	MCS 7	MCS 7
802.11ac	80MHz	MCS 4	MCS 4	MCS 4	MCS 5	MCS 5	MCS 6	MCS 6	MCS 6	MCS 6	MCS 6
802.11ac	160MHz	MCS 3	MCS 3	MCS 3	MCS 4	MCS 4	MCS 4	MCS 5	MCS 5	MCS 6	MCS 6

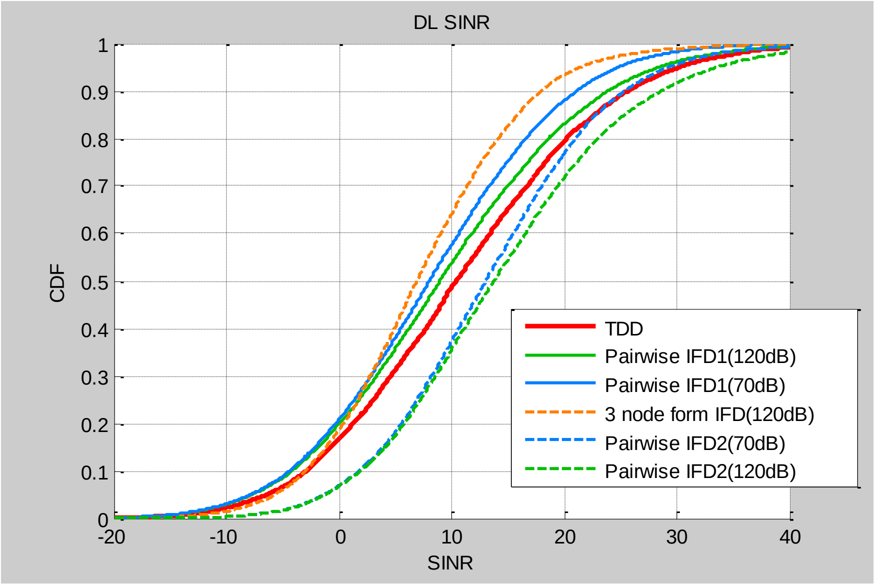
	SNR in dB	31	32	33	34	35	36	37	38	39	40
802.11b	20MHz	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3
802.11a/g	20MHz	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7
802.11n	20MHz	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7
802.11n	40MHz	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7
802.11ac	20MHz	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9
802.11ac	40MHz	MCS 7	MCS 8	MCS 8	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9
802.11ac	80MHz	MCS 7	MCS 7	MCS 7	MCS 7	MCS 8	MCS 8	MCS 9	MCS 9	MCS 9	MCS 9
802.11ac	160MHz	MCS 6	MCS 6	MCS 6	MCS 7	MCS 7	MCS 7	MCS 7	MCS 8	MCS 8	MCS 9

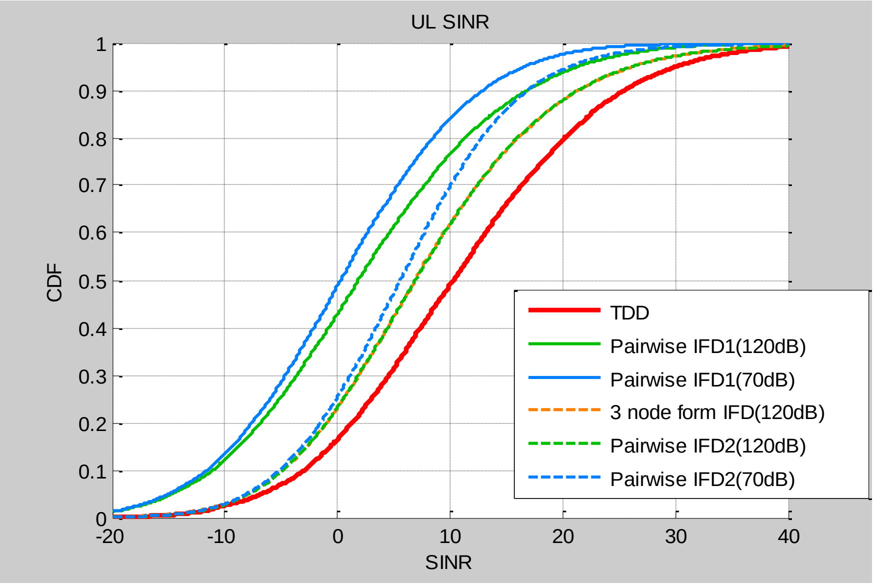
	SNR in dB	41	42	43	44	45	46	47	48	49	50
802.11b	20MHz	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3	MCS 3
802.11a/g	20MHz	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7
802.11n	20MHz	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7
802.11n	40MHz	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7	MCS 7
802.11ac	20MHz	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9
802.11ac	40MHz	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9
802.11ac	80MHz	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9
802.11ac	160MHz	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9	MCS 9

Residential Scenario

❖ Other Simulation Results (2)

- SINR



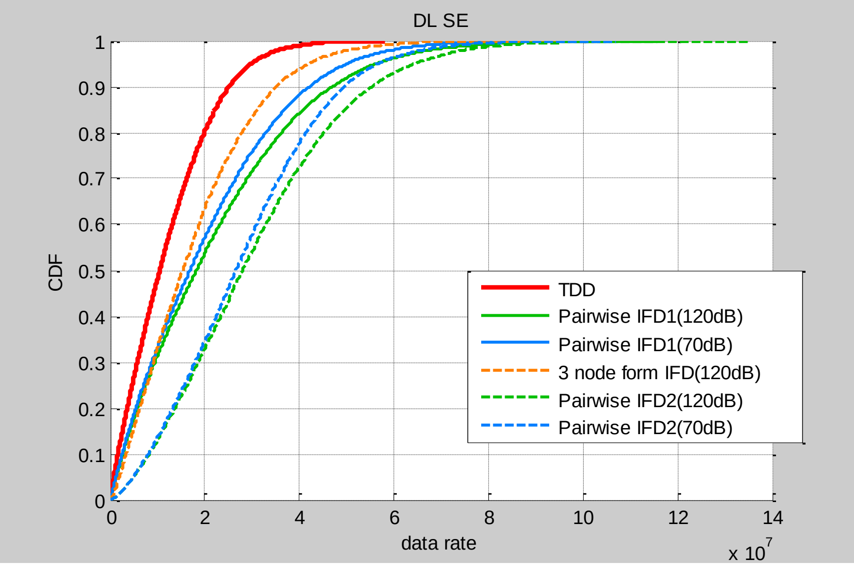


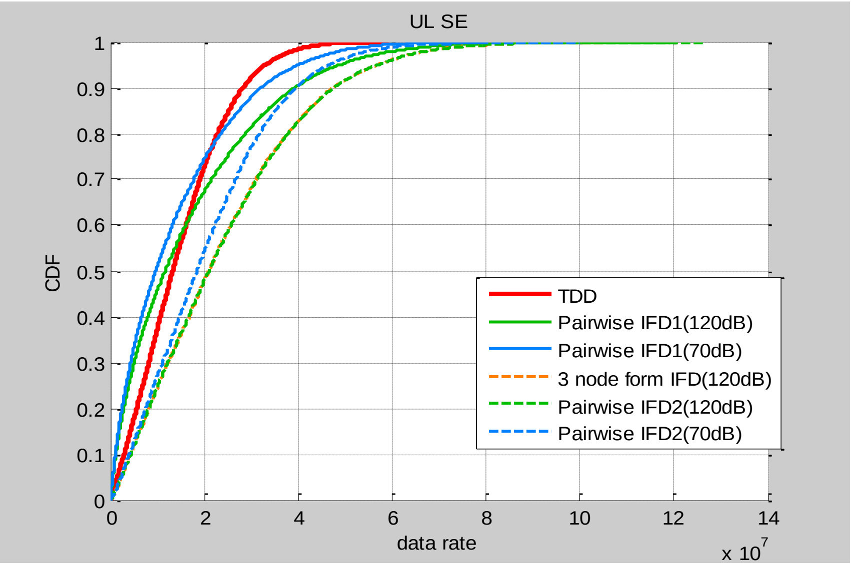
- **DL**
  - with 120 dB SIC, the SINR of pairwise IFD ≈ TDD
  - 5 dB gain with SSC
- **UL**
  - Increase of CCI between APs,
  - Both IFD schemes show inferior performance to TDD even with 120 dB SIC

Residential Scenario

❖ Other Simulation Results (3)

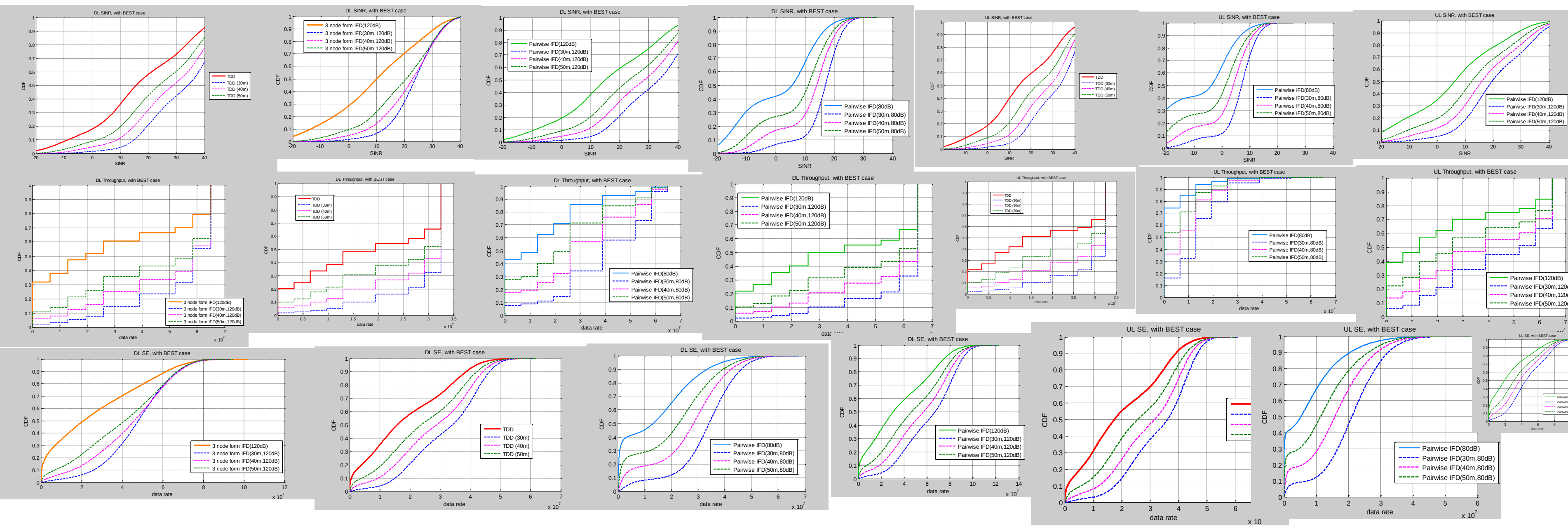
- Spectral Efficiency





Outdoor Large BSS Scenario

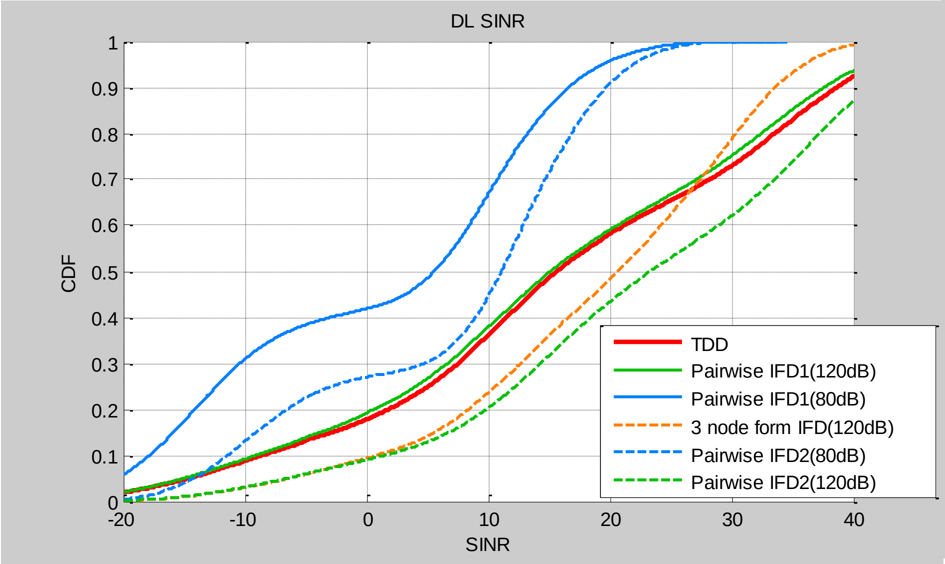
❖ Other Simulation Results (1) (SSC, 1.SINR, 2. Thr, 3.SE)

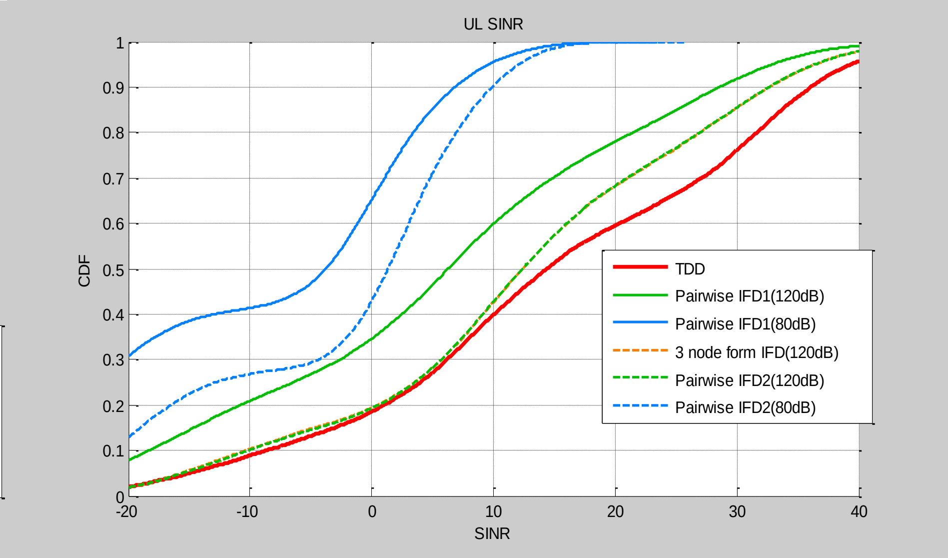


Outdoor Large BSS Scenario

❖ Other Simulation Results (2)

- SINR





Outdoor Large BSS Scenario

❖ Other Simulation Results (2)

- Spectral Efficiency