A Survey on Wireless Full-Duplex: Research and Development Tracks

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Outline

- Full-duplex operation
- Incorporating FD into future systems
- Our cooperation and interface
- Conclusion

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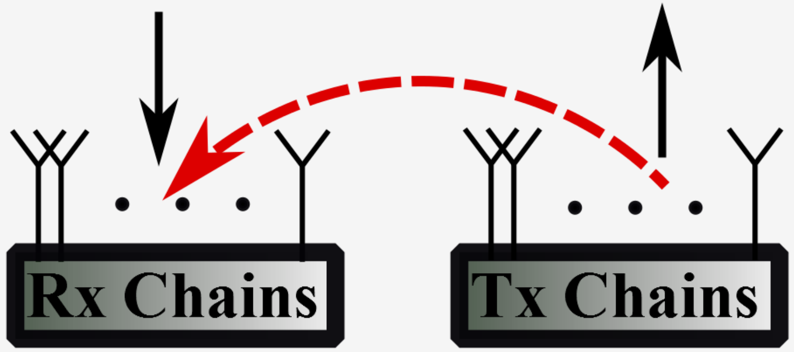
Full-Duplex Operation

- Full-duplex: simultaneous transmission and reception using the same channel

Full-duplex transceiver:



- Challenge: Strong loopback self-interference must be suppressed
  - Limited dynamic range in Tx and Rx
    - E.x., DAC and ADC accuracy, phase noise, I-Q imbalance,…
  - Inaccurate channel knowledge
    - Results in imperfect interference estimation

➡ **Full-duplex communication was known to be infeasible**

Motivation

- **What do we gain via full-duplex?** [CHJKLM], [JCKBSSLK]
  - Bi-directional communication
    - Improved resource efficiency (theoretically by factor of two)
    - Effective feedback channel (CSI-T, Adaptive constellation,..)
    - Enhanced physical layer security, …

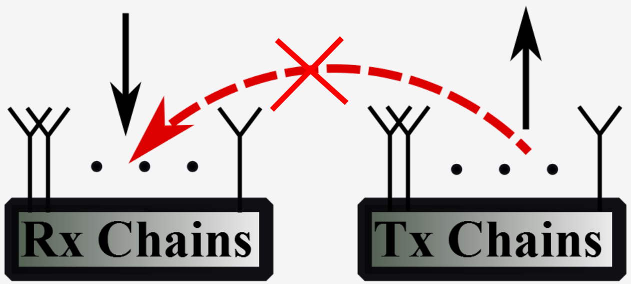
    ➡ Enhanced physical layer function
  - Continuous sensing and presence in the environment
    - No hidden (exposed) terminal problem
    - Improved primary detection

    ➡ Enhanced access layer function
  - Continuous transmission and reception ability
    - Reduced round trip time, reduced network congestion

    ➡ Enhanced network layer function

Full-Duplex Operation

- Recent advances have provided reasonable isolation among Tx and RX antennas via
  - Antenna design and placement
  - RF cancellation circuit design
  - Digital processing methods
  - …



- **Example result:** 110 dB for bandwidth of 80MHz [BMK]
  - Compliant with WiFi 802.11ac
  - Suppression down to the receiver noise floor

➡ FD is seriously considered as a possibility for 5G and beyond!

[BMK] D. Bharadia, E. McMilin, S. Katti. Full Duplex Radios. *ACM 2013.*

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- Full-duplex operation
- Incorporating FD into future systems
- Our cooperation and interface
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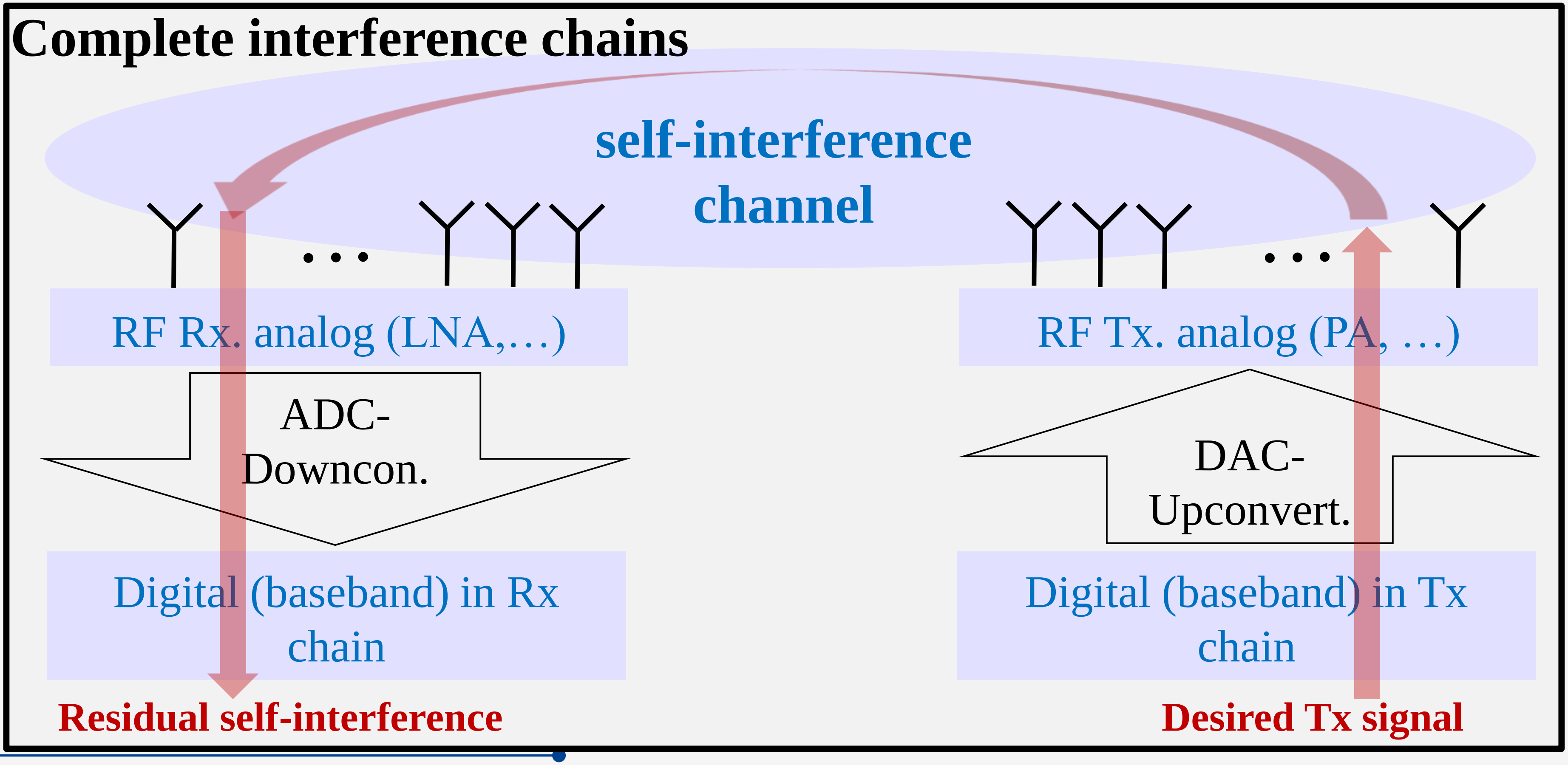
FD for Future Generations

Required research & development tracks to incorporate FD into future standards:

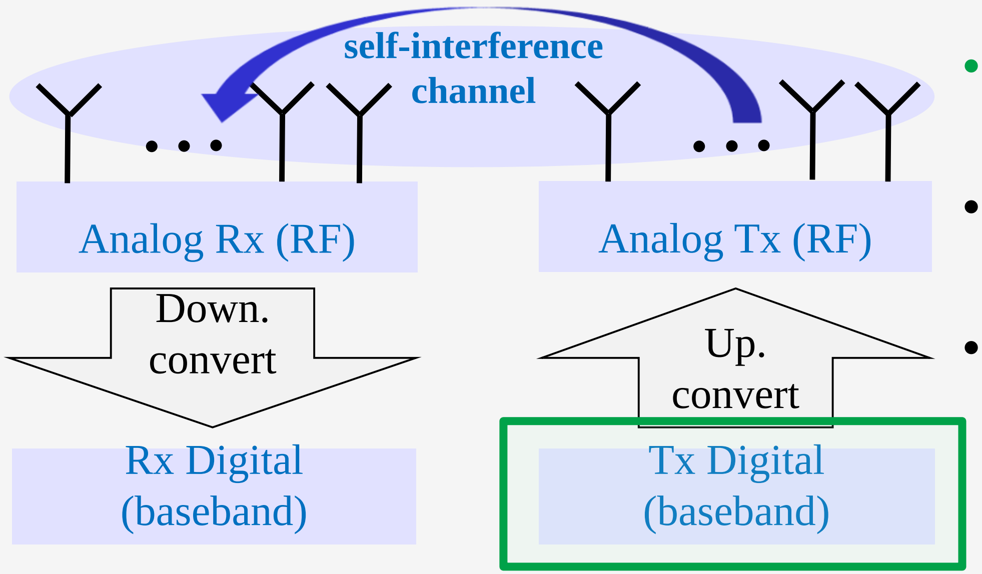
- Feasibility, hardware realization
- Where, how, and how much can this be useful ?
  - Distinguish standards/usecases that benefit from FD
  - Update the classic designs for the new system
  - Theoretical bounds and achievable performance gains
- Hardware & software integration

- **FD research tracks:**
  - Feasibility, hardware realization
  - Self-interference suppression



Feasibility, Hardware Realization

- Self-interference suppression – Tx chain, digital domain



- Null-steering in time and frequency domain [RBHWWW:11], [HLMCG], …
- Keep average interference power within a safe range [TM13], [ZTLH12], …
- Incorporate the spatial characteristics of the residual self-interference in Tx side [DMBS], [ZTH13W], …

[DMBS] B. Day, A. Margetts, D. Bliss, and P. Schniter. Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range. *IEEE Tran. Sig. Proc.*, 2012.

[ZTH13W] J. Zhang, O. Taghizadeh, and M. Haardt, "Transmit Strategies for Full-Duplex Point-to-Point Systems with Residual Self-Interference" *17th International ITG Workshop on Smart Antennas - WSA 2013*

[TM13] O. Taghizadeh, R. Mathar "Full-Duplex Decode-and-Forward Relaying with Limited Self-Interference Cancellation" *ITG WSA 2014*

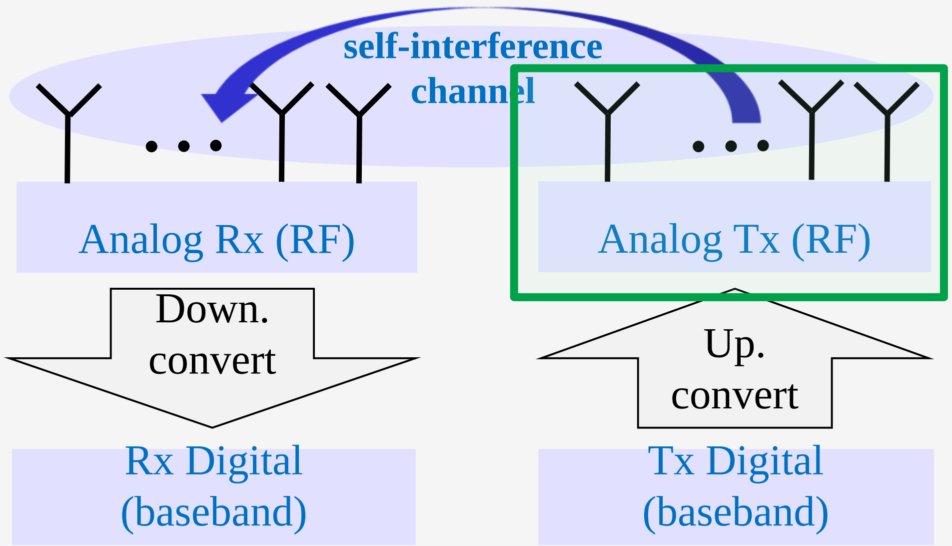
[ZTLH12] J. Zhang, O. Taghizadeh, J. Luo, and M. Haardt, "Full duplex wireless communications with partial interference cancellation", *Proc. of the 46th Asilomar Conference on Signals, Systems, and Computers, (Pacific Grove, CA, Nov. 2012*.

[RBHWWW:11] T. Riihonen, A. Balakrishnan, K. Haneda, S.Wyne, S.Werner and R.Wichman. Optimal eigenbeamforming for suppressing self-interference in full-duplex MIMO relays. Proc. Information Sciences and Systems (CISS), Annual Conference on, 2011.

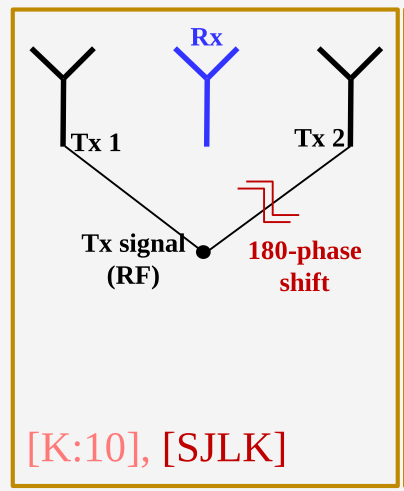
[HLMCG] Y. Hua, P. Liang, Y. Ma, A.C. Cirik, and Q. Gao, "A Method for Broadband Full-Duplex MIMO Radio" *IEEE Signal Processing Letters*, Dec 2012.

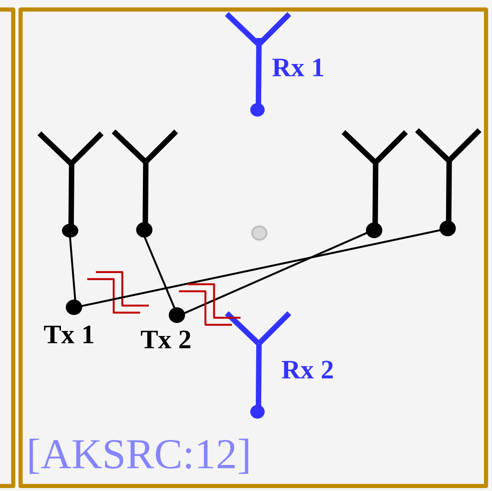
Feasibility, Hardware Realization

- Self-interference suppression – Tx chain, RF domain



- Antenna cancellation: Null-steering with auxilliary propagation in RF: [SJLK], [K:10], [AKSRC:12]





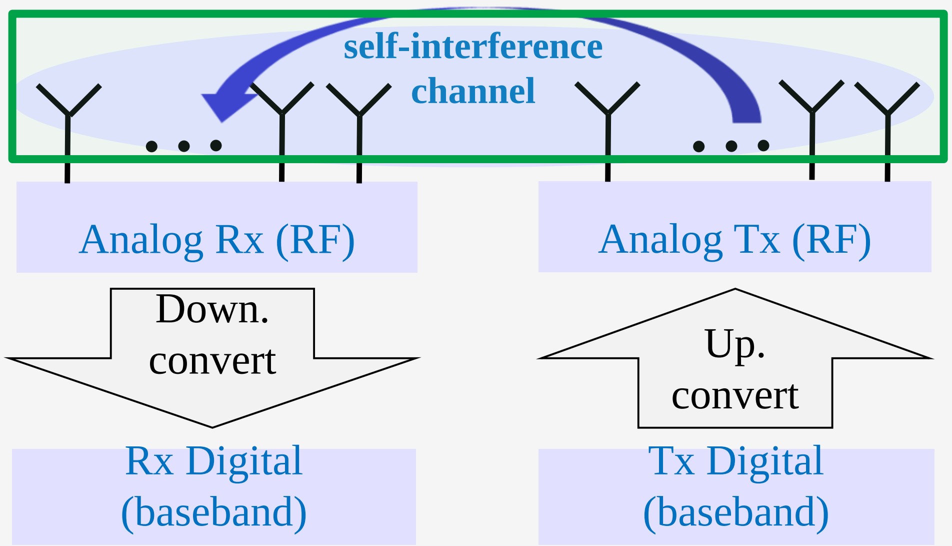
[AKSRC:12] Ehsan Aryafar, Mohammad (Amir) Khojastepour, Karthikeyan Sundaresan, Sampath Rangarajan, and Mung Chiang "MIDU: Enabling MIMO Full Duplex" MobiCom'12, August 22–26, 2012.

[K:10] A. K. Khandani, "Methods for spatial multiplexing of wireless two-way channels," Oct. 19 2010.

[SJLK] J. I. Choi, M. Jain, K. S. P. Levis, and S. Katti. Achieving single channel, full-duplex wireless communication. In *Proc. 16th Annual Int. Conf. Mobile Computing and Networking (Mobicom 2010)*, Chicago, IL, Sept. 2010.

Feasibility, Hardware Realization

- Self-interference suppression – Passive cancellation



➡ Passive interference cancellation

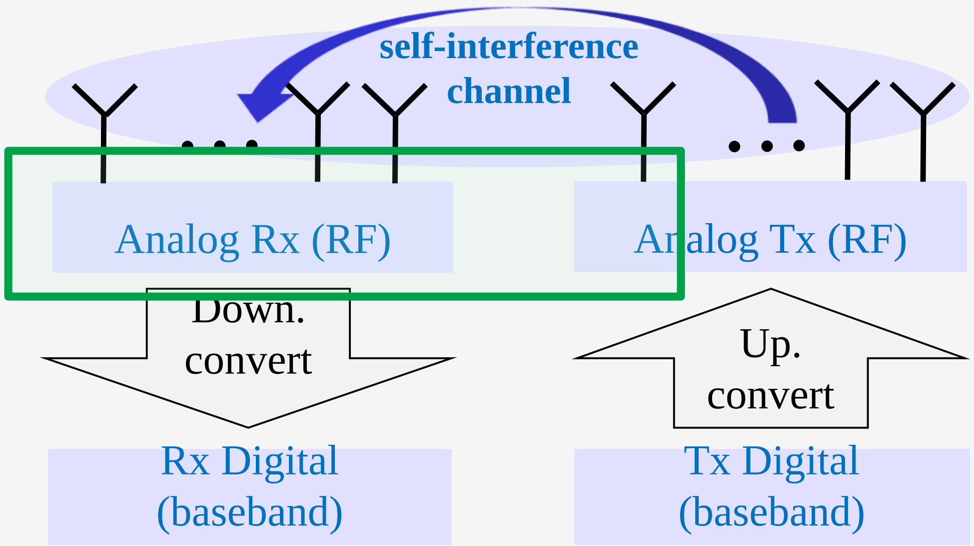
- Proper placement of Rx and Tx antennas to reduce the direct interference paths (natural isolation [DS:10], [CJLK])
- Exploit directivity of Tx and Rx (directional diversity [EDDS:11])

[EDDS:11] E. Everett, M. Duarte, C. Dick, and A. Sabharwal. Empowering full-duplex wireless communication by exploiting directional diversity. In *Proc. 44th Asilomar Conf. Signals, Systems, and Computers (Asilomar 2011)*, Pacific Grove, CA, 2011.

[DS:10] M. Duarte and A. Sabharwal. Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results. In Proc. 44th Asilomar Conf. Signals, Systems, and Computers (Asilomar 2010), Pacific Grove, CA, Nov. 2010.

[CJLK] J. I. Choi, M. Jain, K. S. P. Levis, and S. Katti. Achieving single channel, full-duplex wireless communication. In Proc. 16th Annual Int. Conf. Mobile Computing and Networking (Mobicom 2010), Chicago, IL, Sept. 2010.

- Self-interference suppression – Rx chain, RF domain



- Interference reconstruction via auxiliary chains
  - Rice: [DS:10], [SPS:11]
  - HHI: [AKSHK:14]
- Copying the Tx signal in RF with phase shift and delay:
  - Stanford: BALUN technique [JCKBSSLK], [BMK]

[BMK] D. Bharadia, E. McMilin, S. Katti. Full Duplex Radios. *ACM 2013.*

[JCKBSSLK] M. Jain, J. I. Choi, T. Kim, D. Bharadia, K. Srinivasan, S. Seth, P. Levis, S. Katti, and P. Sinha. Practical, real-time, full duplex wireless. In *Proc. 17th Annual Int. Conf. Mobile Computing and Networking (Mobicom 2011)*, Las Vegas, NV, Sept. 2011.

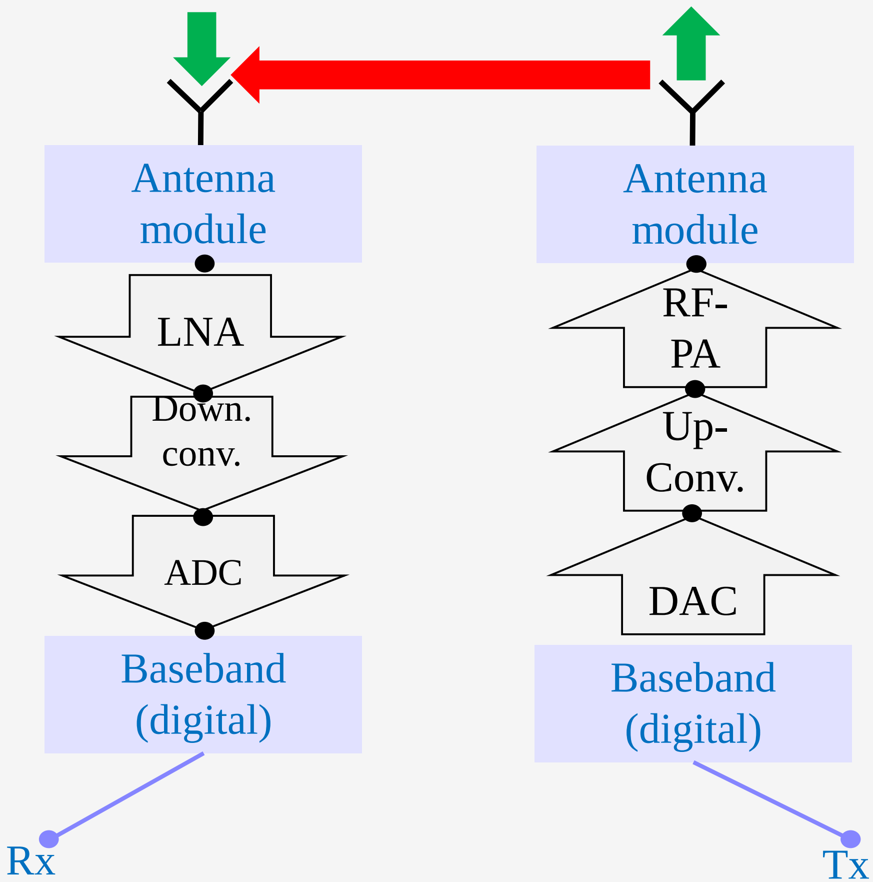
[DS] M. Duarte and A. Sabharwal. Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results. In Proc. 44th Asilomar Conf. Signals, Systems, and Computers (Asilomar 2010), Pacific Grove, CA, Nov. 2010.

[AKSHK:14] Askar, R.; Kaiser, T.; Schubert, B.; Haustein, T.; Keusgen, W., "Active self-interference cancellation mechanism for full-duplex wireless transceivers," Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2014

[SPS:11] A. Sahai, G. Patel, and A. Sabharwal. Pushing the limits of full-duplex: Design and real-time implementation. Technical report, Department of Electrical and Computer Engineering, Rice University, 2011.

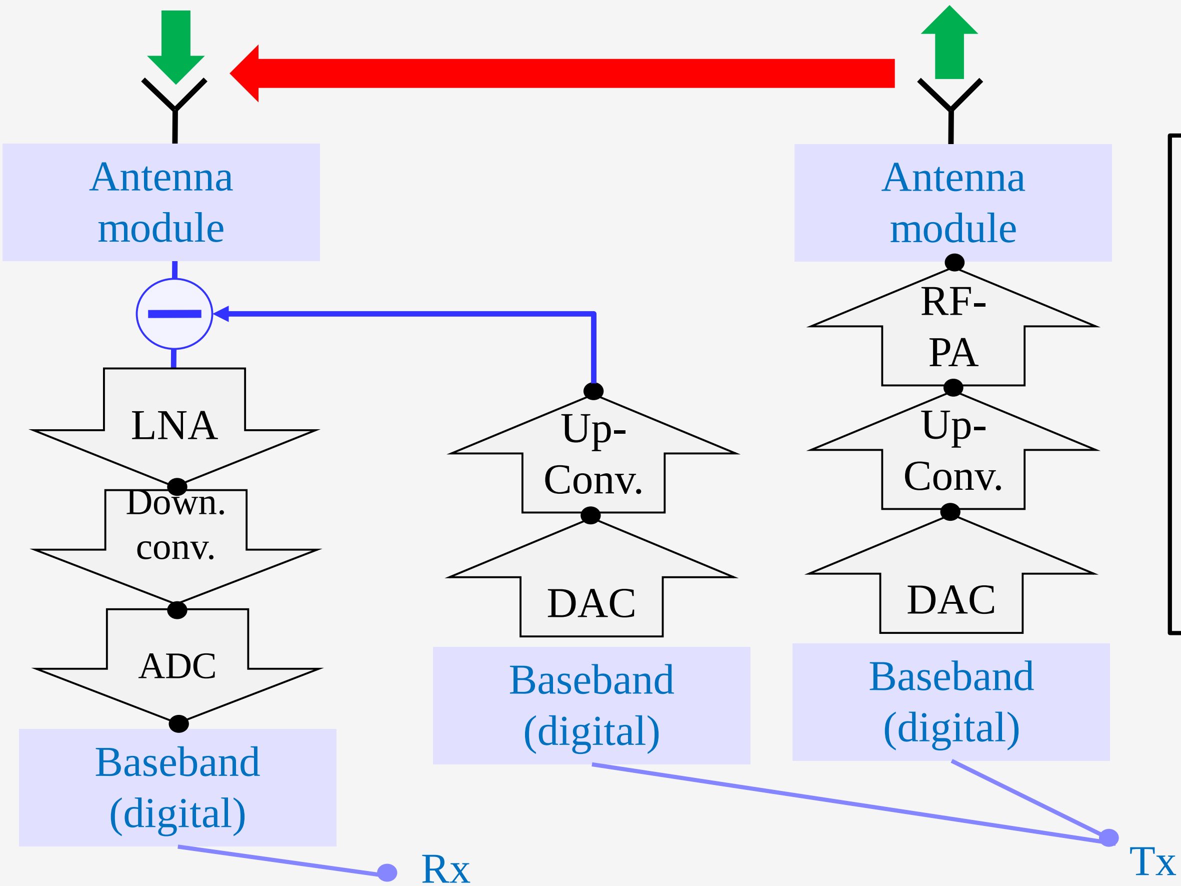
Feasibility, Hardware Realization

- Self-interference suppression – Rx chain, RF domain (cont.)



Feasibility, Hardware Realization

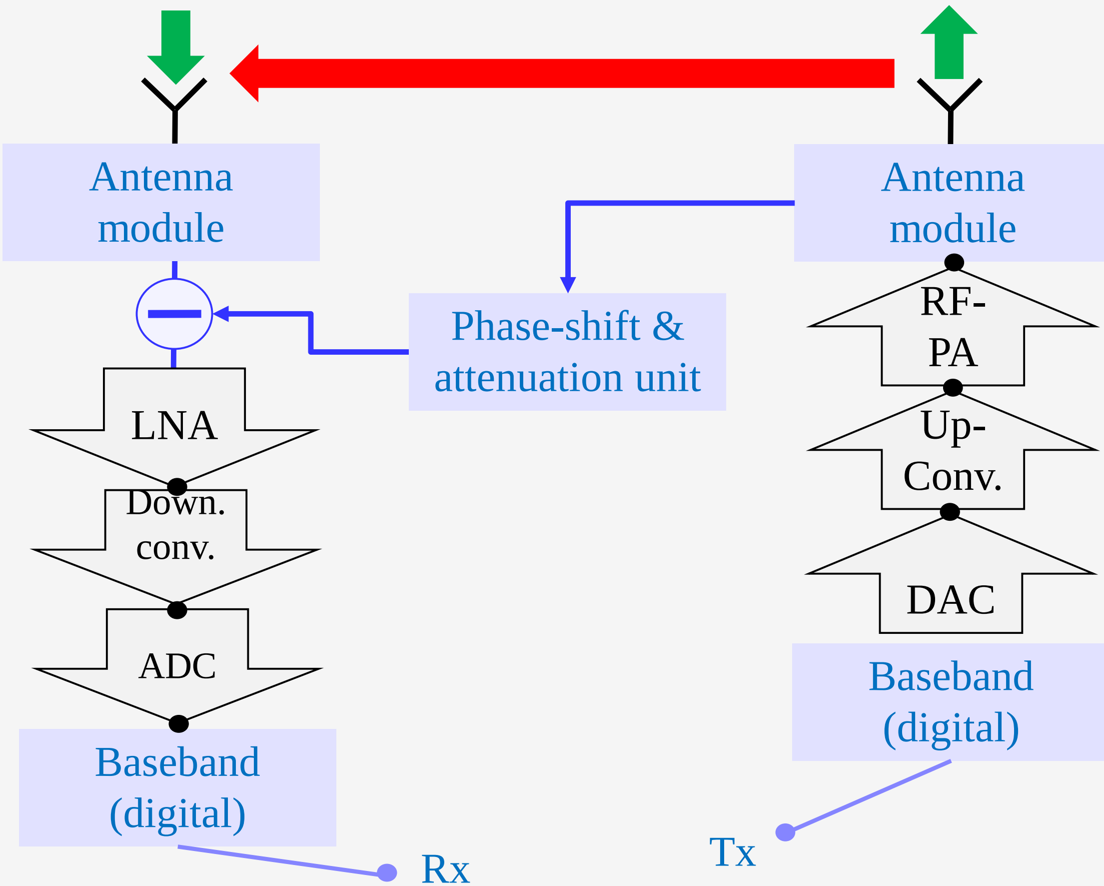
- Self-interference suppression – Rx chain, RF domain (cont.)



- Interference reconstruction via auxiliary chains
  - Rice: [DS:10], [SPS:11]
  - HHI: [AKSHK:14]
- Challenge: Tx noise, more cost
- Around 85dB suppression is reported

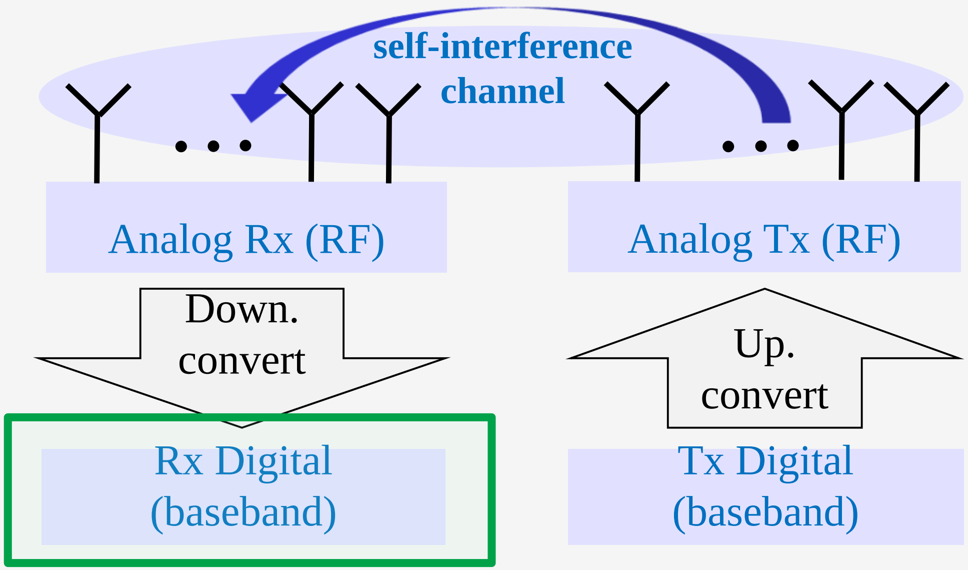
Feasibility, Hardware Realization

- Self-interference suppression – Rx chain, RF domain (cont.)



- Copying the Tx signal in RF with phase shift and delay:
  - Stanford: BALUN technique [JCKBSSLK], [BMK]
- Challenge: Accurate phase-shift & attenuation is needed
- Around 110dB suppression is reported

- Self-interference suppression – Rx chain, digital domain



- Dealing with remaining interference:
  - Compensating PA non-lin effect: [BMK:13], [AKSHK:14], …
  - Joint Tx-Rx strategy, Rx antenna selection: [CWRH:14], [RWW:11], …

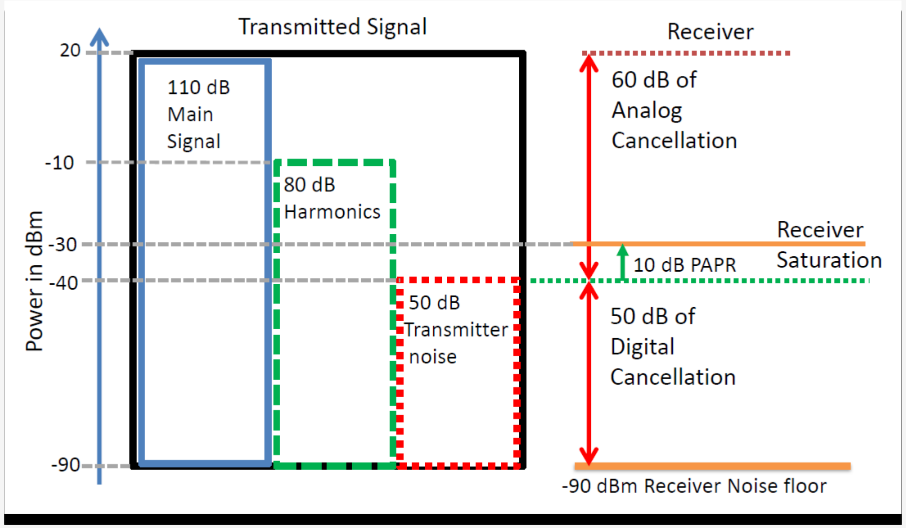
[BMK:13] D. Bharadia, E. McMilin, S. Katti. Full Duplex Radios. *ACM 2013*.

[AKSHK:14] Askar, R.; Kaiser, T.; Schubert, B.; Haustein, T.; Keusgen, W., "Active self-interference cancellation mechanism for full-duplex wireless transceivers," Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2014

[CWRH:14] Ali Cagatay Cirik, Rui Wang, Yue Rong§ and Yingbo Hua , MSE Based Transceiver Designs for Bi-directional Full-Duplex MIMO Systems, SPAWC

[RWW:11] Riihonen, T.; Werner, S.; Wichman, R., "Mitigation of Loopback Self-Interference in Full-Duplex MIMO Relays," *Signal Processing, IEEE Transactions on* , vol.59, no.12, pp.5983,5993, Dec. 2011

- Self-interference suppression – to conclude:
  - Several attempts for cancelling out the self-interference
  - Over 100 dB of suppression is feasible!
  - The cancellation must be done simultaneously in several domains.
    - Single-domain cancellation methods do not bring enough suppression



Levels of suppression in different layers, [BMK:13]

[BMK:13] D. Bharadia, E. McMilin, S. Katti. Full Duplex Radios. *ACM 2013.*

FD for Future Generations

Required research & development tracks to incorporate FD into future standards:

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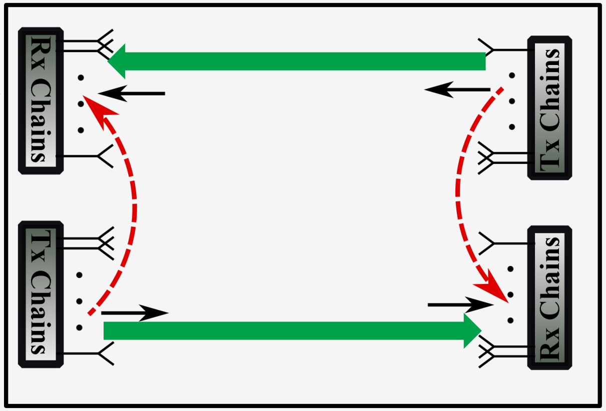
  - Theoretical bounds and achievable performance gains
- Hardware & software integration

Example Use-Case: FD P2P

- Example FD use-case: FD point to point



➡ Enhanced spectral efficiency, real-time feedback channel, improved access layer function, …

- – P2P FD modeling, achievable rates [DMBS:12]
- – Interference zero-forcing and power adjustment (HD vs FD trade-off) [ZTH13W]
- – Sum rate enhancement [ZTLH12], [CZHH:14]
- – Coping with CSI imperfection [ZTH:13], [CZHH:14]

[ZTH:13] J. Zhang, O. Taghizadeh, M. Haardt, Robust Transmit Beamforming Design for Full-Duplex Point-to-Point MIMO Systems, Proceedings: Wireless Communication Systems (ISWCS 2013), Proceedings of the Tenth International Symposium on, 2013.

[CZHH:14] A. C. Cirik, J. Zhang, M. Haardt, and Y. Hua, ``Sum-rate maximization for bi-directional full-duplex MIMO systems under multiple linear constraints," in *Proc. 15-th IEEE Int. Workshop on Signal Processing Advances in Wireless Communications (SPAWC 2014).*

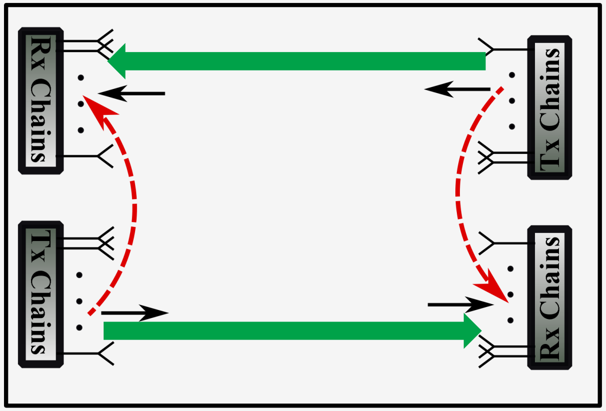
[ZTLH12] J. Zhang, O. Taghizadeh, J. Luo, and M. Haardt, "Full duplex wireless communications with partial interference cancellation", *Proc. of the 46th Asilomar Conference on Signals, Systems, and Computers, (Pacific Grove, CA, Nov. 2012*.

[ZTH13W] J. Zhang, O. Taghizadeh, and M. Haardt, "Transmit Strategies for Full-Duplex Point-to-Point Systems with Residual Self-Interference" *17th International ITG Workshop on Smart Antennas - WSA 2013*

[DMBS:12] B. Day, A. Margetts, D. Bliss, and P. Schniter. Full-duplex bidirectional MIMO: Achievable rates under limited dynamic range. *IEEE Tran. Sig. Proc.*, 2012.

Example Use-Case: FD P2P

- Example FD use-case: FD point to point
  - Update the medium access layer protocols for FD nodes
    - MAC protocol IEEE 802.11: FD-MAC [SPS11], [SGPRBK11], …
    - Access layer performance analyze for FD wireless LAN [OB12]
    - Adaptive sensing-transmission-reception: [AK:14] , [CZZ:11]



[CZZ:11] Wenchi Cheng; Xi Zhang; Hailin Zhang, "Full duplex spectrum sensing in non-time-slotted cognitive radio networks," MILITARY COMMUNICATIONS CONFERENCE, 2011 - MILCOM 2011 , vol., no., pp.1029,1034, 7-10 Nov. 2011

[AK:14] Afifi, W.; Krunz, M., "Adaptive transmission-reception-sensing strategy for cognitive radios with full-duplex capabilities," Dynamic Spectrum Access Networks (DYSPAN), 2014 IEEE International Symposium on , vol., no., pp.149,160, 1-4 April 2014

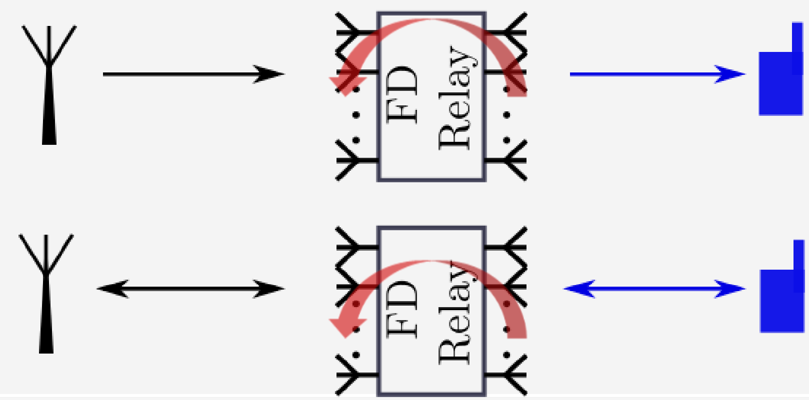
[OB12] Oashi, S.; Bandai, M., "Performance of Medium Access Control Protocols for Full-Duplex Wireless LANs," *Information and Telecommunication Technologies (APSITT), 2012 9th Asia-Pacific Symposium on* , vol., no., pp.1,4, 5-9 Nov. 2012.

[SGPRBK11] N. Singh, D. Gunawardena, A. Proutiere, B. Radunovic, H. V. Balan, P. Key “Efficient and fair MAC for wireless networks with self-interference cancellation” WiOpt May. 2011.

[SPS11] A. Sahai, G. Patel, and A. Sabharwal. Pushing the limits of full-duplex: Design and real-time implementation. Technical report, Department of Electrical and Computer Engineering, Rice University, 2011.

Example Use-Case: FD Relaying

- Example FD use-case: FD relaying



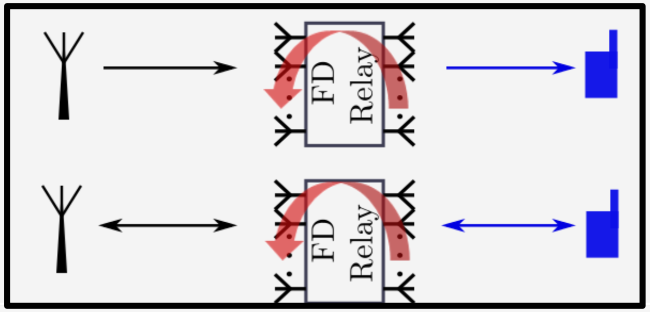
One-way, FD relay

Two-way, FD relay

- Reduced time slots ➡ higher efficiency, lower delay.
- **One-way** relaying protocol ➡ Factor of two in spectral efficiency, end users remain HD (HD user-compatible)
- **Two-way** relaying protocol ➡ Continuous Rx, Tx in both sides, Factor of four in spectral efficiency, end-users need to be FD (HD user-incompatible)

Example Use-Case: FD Relaying

- Example FD use-case: FD relaying (cont.)
  - Various FD relaying scenarios have been studied:
    - Sum rate maximization for FD, amplify-and-forward (AF) relaying [ZTH:13],
    - Sum rate maximization for FD, decode-and-Forward (DF) relaying [DMBS:12],
    - Digital interference loop cancellation for FD AF relays [RWW:11], [RWW:09]
    - Efficient FD DF relaying with imperfect CSI [TM:14F], [TM:14R]



[TM:14R] O. Taghizadeh, R. Mathar, Robust Multi-User Decode-and-Forward Relaying with Full-Duplex Operation, Proceedings: *The Eleventh International Symposium on Wireless Communication Systems (ISWYS 2014)*, Barcelona, Spain, September 2014.

[TM:14F] O. Taghizadeh, R. Mathar, Full-Duplex Decode-and-Forward Relaying with Limited Self-Interference Cancellation, Proceedings: *18th International ITG Workshop on Smart Antennas 2014 (WSA 2014)*, Erlangen, Germany, March 2014.

[RWW:09] T. Riihonen, S. Werner, and R. Wichman. Spatial loop interference suppression in full-duplex MIMO relays. Proc. Signals, Systems and Computers, Forty-Third Asilomar Conference on, 2009.

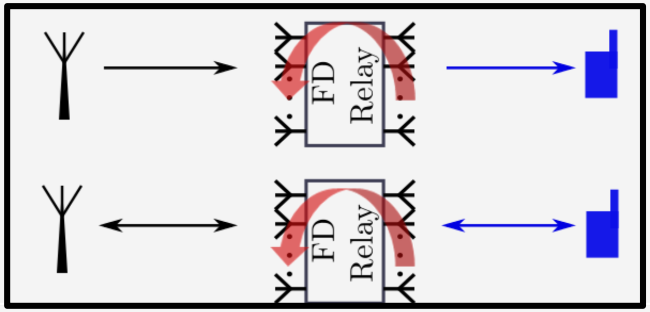
[RWW:11] T. Riihonen, S. Werner, and R. Wichman. Mitigation of loopback self-interference in full-duplex MIMO relays. IEEE Trans. on Signal Processing, 2011

[DMBS:12] B. Day, A. Margetts, D. Bliss, and P. Schniter. Full-duplex MIMO relaying: Achievable rates under limited dynamic range. Selected Areas in Communications, IEEE Journal on, 30:1541–1553, Sept. 2012.

[ZTH:13] J. Zhang, O. Taghizadeh, and M. Haardt, "Transmit Strategies for Full-Duplex Point-to-Point Systems with Residual Self-Interference" *17th International ITG Workshop on Smart Antennas - WSA 2013*

Example Use-Case: FD Relaying

- Example FD use-cases: FD relaying (cont.)
  - Multi-user operation with FD DF Relay [TM:14R],
  - Cooperative mechanisms for distributed FD AF relaying [TM:14C], [KSSC:12], [KIAS:13], …
  - Interference alignment schemes using FD relays [MM13], [MCM:14] …



[MCM:14] H. Maier, A. Chaaban, R. Mathar, Degrees of Freedom of the MIMO 3-Way Channel, to appear: Proceedings: IEEE International Symposium on Information Theory and Its Applications (ISITA 2014), Melbourne, VIC, Australia, ...

[MM13] Maier, H.; Mathar, R., "Cyclic Interference Neutralization on the full-duplex relay-interference channel," *Information Theory Proceedings (ISIT), 2013 IEEE International Symposium on* , vol., no., pp.2309,2313, 7-12 July 2013

[KSSC:12] Krikidis, I.; Suraweera, H.A.; Smith, P.J.; Chau Y., "Full-Duplex Relay Selection for Amplify-and-Forward Cooperative Networks," *Wireless Communications, IEEE Transactions on* , vol.11, no.12, pp.4381,4393, December 2012

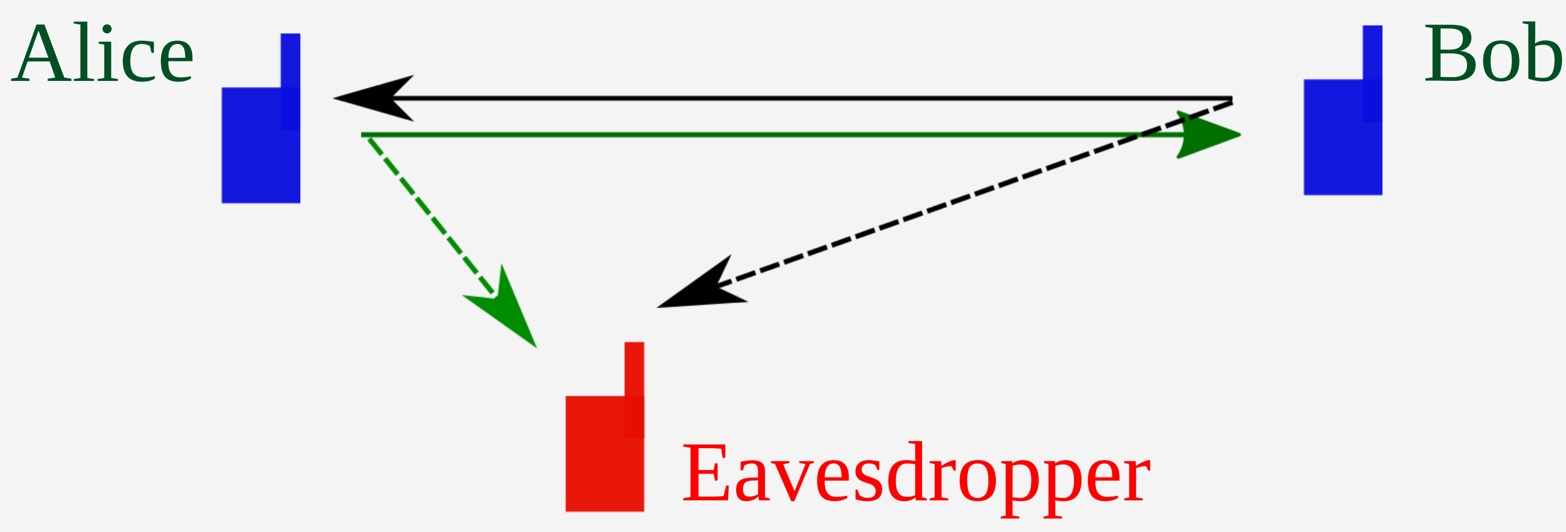
[TM:14C] O. Taghizadeh, R. Mathar, Cooperative Strategies for Distributed Full-Duplex Relay Networks with Limited Dynamic Range, to appear: Proceedings: *Wireless for Space and Extreme Environments (WiSEE), 2014 IEEE International Conference on*, Noordwijk, Netherlands (to appear)

[TM:14R] O. Taghizadeh, R. Mathar, Robust Multi-User Decode-and-Forward Relaying with Full-Duplex Operation, Proceedings: *The Eleventh International Symposium on Wireless Communication Systems (ISWYS 2014)*, Barcelona, Spain, September 2014.

[KIAS:13] Mohammad Khafagy, Amr Ismail, Mohamed-Slim Alouini, and Sonia A, On the Outage Performance of Full-Duplex Selective Decode-and-Forward Relaying, IEEE COMMUNICATIONS LETTERS, VOL. 17, NO. 6, JUNE 2013

Ex. Use-Case: Wiretap Channel

- Example FD use-case: FD wiretap channel



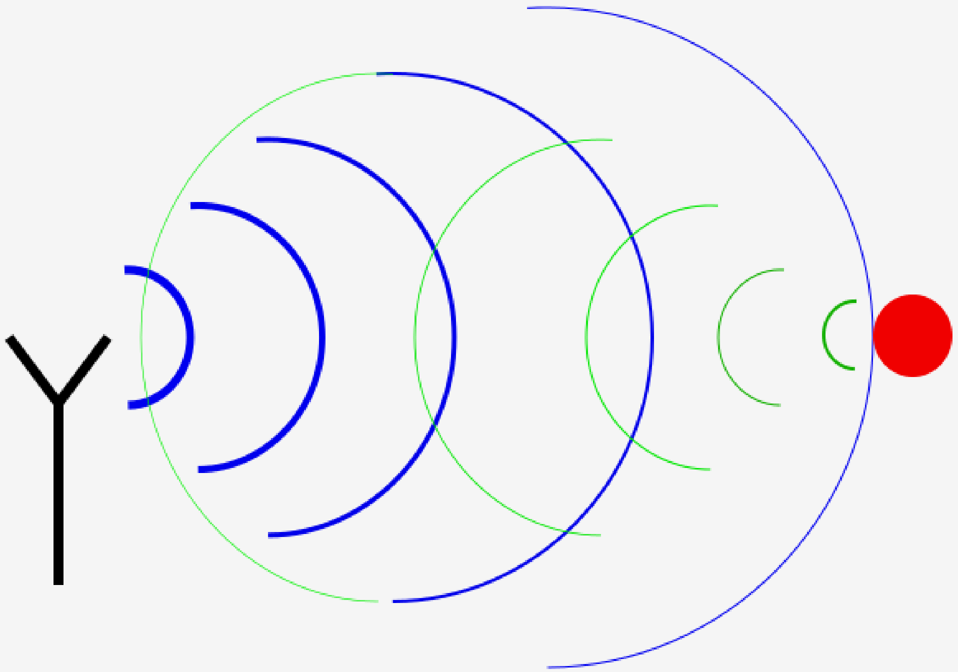
- New achievable secrecy rates with FD operation,
  - Achievable bounds and performance analyze [GKYG10],
  - Optimal power adjustment and Tx strategy [ZKLPO:13], …

[ZKLPO:13] G. Zheng, I. Krikidis, J. Li, A. P. Petropulu , and B. Ottersten, Improving Physical Layer Secrecy Using Full-Duplex Jamming Receivers, IEEE TRANS. ON SIG. PROC. , 2013

[GKYG10] A. E. Gamal, O. Koyluoglu, M. Youssef, and H. E. Gamal, "New achievable secrecy rate regions for the two way wiretap channel." *Information Theory Workshop (ITW). IEEE, 2010.*

Example Use-Case: FD Radar

- Example FD use-case: FD radar



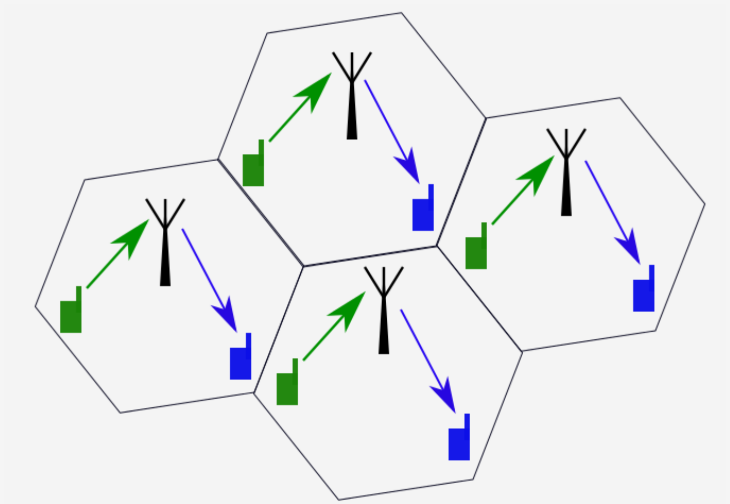
- Significantly higher observation resolution with FD capability
  - Multiple object detection and classification via iterative cancellation [BJK13] -

[BJK13] D. Bharadia, K. R. Joshi, and S. Katti. "Full Duplex Backscatter." *Sigcomm 2013*.

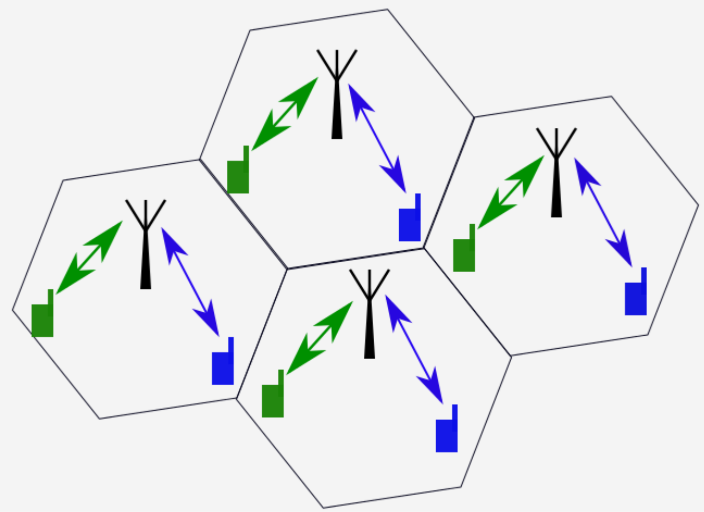
Example Use-Case: FD Base-Station

- Example FD use-case: FD operation in base-station:

FD base-station, HD users:



FD base-station, FD users:



- More flexible resource allocation, higher resource efficiency
  - Multi-user MIMO strategies for downlink and uplink: [NTPL13]

[NTPL13] D. Nguyen, L. N. Tran, P. Pirinen, M. Latva-aho, "Precoding for Full Duplex Multiuser MIMO Systems: Spectral and Energy Efficiency Maximization," *Signal Processing, IEEE Transactions on* , vol.61, no.16, pp.4038,4050, Aug.15, 2013

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Our Cooperation and Interface

- Our expertise: Signal processing
  - System optimization for various scenarios with FD operation
  - Theoretical bounds on system performance,
  - Rx-Tx baseband design,
  - …

- Main convergence points:
  - System model, model verification,
  - Periodic meetings to share findings and updates,
  - Hardware, software integration.

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To Conclude..

- FD is a new, promising research area!
- High hopes for our cooperation!

Thanks for your attention!