Towards the Next Stage Evolution of Massive MIMO for 5G and Beyond:

A Cost-Effective Perspective

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Outline

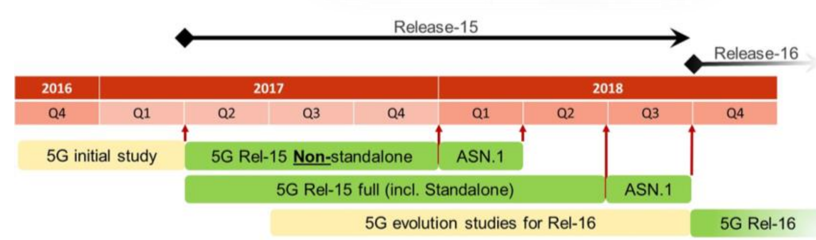
- **Massive MIMO: The 1st Step in the 5G Evolution**
- Cost Considerations & Solution Approaches
- Massive MIMO Enabled Wireless Backhaul for HetNets
- Design of Cost-Efficient Massive MIMO Under Practical Hardware Constraints
- Summary

5G is Coming!

- **Bloomberg: Verizon CEO announced rolling out of 5G services in Oct., 2018**
  - The 1st carrier in the world to get to 5G cellular. ***Sort of.***
  - Limited to home broadband services in ***4 cities***.
  - Early 5G launch uses ***non-industry-standard*** technology.
- **5G timeline of other major carriers in U.S.**
  - AT&T: Offer 5G as a true mobile service by the end of 2018.
  - T-Mobile: Broader commercial service available early 2019.
  - Sprint & LG: Promising the first 5G smartphone.

5G is Coming! (Cont'd)

- Implications of Verizon launching 5G
  - Incomplete version, only provides limited 5G services
  - Not ready for large-scale rollout, concerns about technological maturity, cost, etc.
  - Still much to do for industry standardization
- Other limiting factors
  - Availability of mmWave RF
  - Reliability considerations
  - Backhaul/fronthaul crunch
  - ……



5G NR Phase-1: Massive MIMO

- Disruptive technologies for 5G and their technology status
- Massive MIMO: The 1st step in 5G evolution
  - Idea proposed based on MU-MIMO around 2010
  - SDR-based prototypes: Argos (2012), LuMaMi (2014), ARIES (2016), SEU-NUPT-ZZU (2016) etc.
  - Better compatibility with current RAN architecture
  - Commercial trials of the technology started in 2016
  - Already incorporated into 4.5G/pre-5G systems
  - Improves spectral efficiency by up to an order of magnitude

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A Little Bit Fundamentals

- The basic massive MIMO model
  - Uplink (with MF receiver)

$$\mathbf{y}_u = \sqrt{\rho_u}\mathbf{H}\mathbf{x}_u + \mathbf{n}_u$$

$$\mathbf{H}^{\mathrm{H}}\mathbf{H} = \mathbf{D}^{1/2}\mathbf{G}^{\mathrm{H}}\mathbf{G}\mathbf{D}^{1/2} \approx N\mathbf{D}^{1/2}\mathbf{I}_K\mathbf{D}^{1/2} = N\mathbf{D}$$

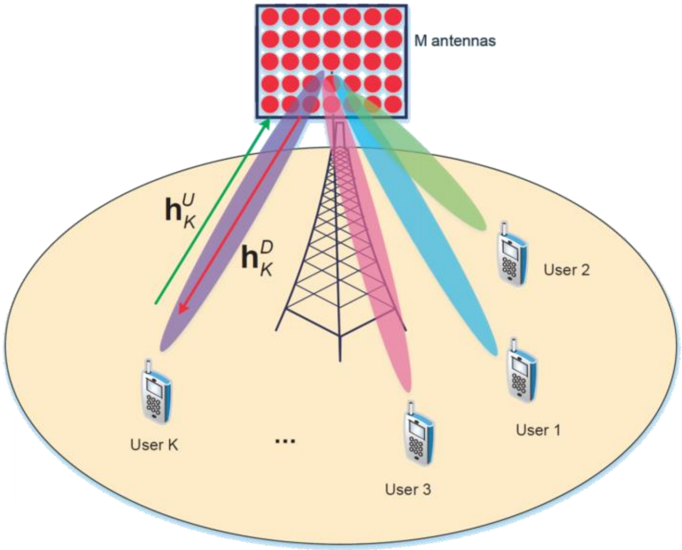
$$\begin{aligned}\mathbf{H}^{\mathrm{H}}\mathbf{y}_u &= \mathbf{H}^{\mathrm{H}}(\sqrt{\rho_u}\mathbf{H}\mathbf{x}_u + \mathbf{n}_u) \\ &\approx N\sqrt{\rho_u}\mathbf{D}\mathbf{x}_u + \mathbf{H}^{\mathrm{H}}\mathbf{n}_u\end{aligned}$$

  - Downlink (with MF precoding)

$$\mathbf{y}_d = \sqrt{\rho_d}\mathbf{H}^{\mathrm{T}}\mathbf{x}_d + \mathbf{n}_d$$

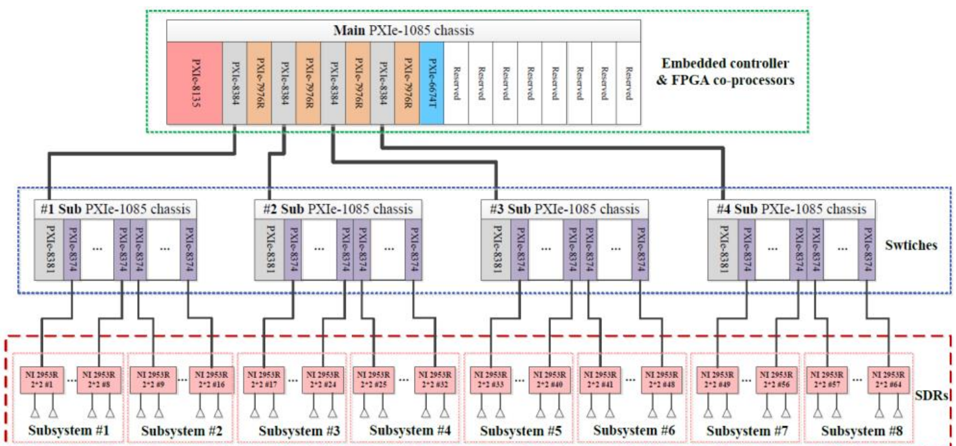
$$\mathbf{x}_d = \mathbf{H}^{*}\mathbf{D}^{-1/2}\mathbf{P}^{1/2}\mathbf{s}_d$$

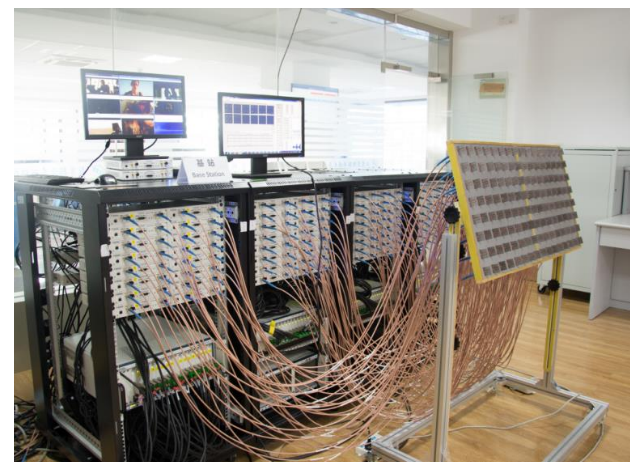
$$\begin{aligned}\mathbf{y}_d &= \sqrt{\rho_d}\mathbf{H}^{\mathrm{T}}\mathbf{H}^{*}\mathbf{D}^{-1/2}\mathbf{P}^{1/2}\mathbf{s}_d + \mathbf{n}_d \\ &\approx \sqrt{\rho_d}N\mathbf{D}^{1/2}\mathbf{P}^{1/2}\mathbf{s}_d + \mathbf{n}_d\end{aligned}$$



Prototyping Massive MIMO

- SDR-based prototypes of massive MIMO
  - A primitive form: Rice Argos based on WARP & PFGA
  - Better integration of FPGA and RF I/O: USRP RIO
    LuMaMi, SEU-NUPT-ZZU





X. Yang, W. Lv, N. Wang, *et. al*, "Design and implementation of a TDD-based 128-antenna massive MIMO prototype system," *China Communications*, vol. 14, no. 12, pp. 162-187, 2017.

The Cost Challenge

- A massive MIMO BS equipment is almost **10×** **more expensive** than an LTE eNodeB!!!!!!
  - Due to the use of large number of antennas and RF chains
  - Cost in baseband digital processing is not dominant
  - Bottleneck for cost cut is in the analog RF part
- Possible technical solution directions
  - Improve implementation efficiency of massive MIMO BSs
  - Reduce manufacture cost of each massive MIMO BS equipment

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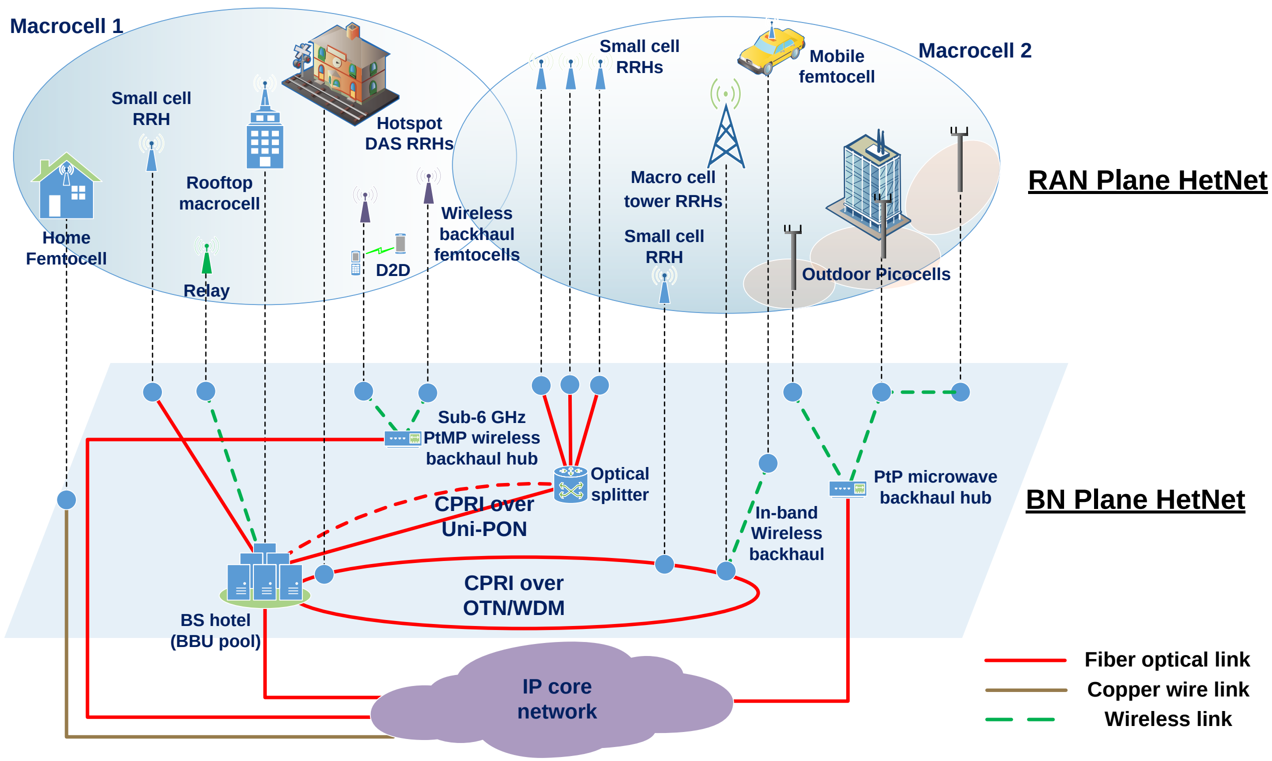
The 5G Backhaul Crunch

- Massive MIMO BS implementation in 5G HetNets
  - Reduced macro-cell density for centralized massive MIMO
  - Ultra-densen small cell networks
- Underlying driving force for wireless backhaul (WB) in 5G small cells
  - Extreme densification of small cell BSs
  - Availability of wired backhaul resources: Backhaul crunch in the 5G era
  - Desirable feature of small cell equipments: Plug-and-play, easy implementation and maintenance, like the white box

The 5G Backhaul Crunch (Cont'd)

- HetNet architecture for both 5G RAN and 5G BN



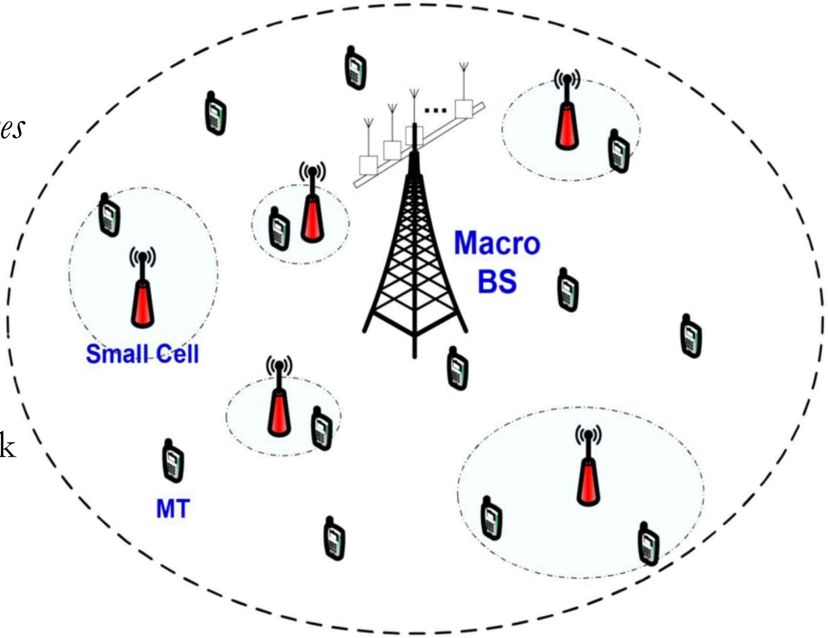
N. Wang, E. Hossain, and V. K. Bhargava, "Backhauling 5G small cells: A radio resource management perspective," *IEEE Wireless Communications*, vol. 22, no. 5, pp. 41-49, 2015.

Massive MIMO IB-WB

- In-band wireless backhaul provided by massive MIMO macro BS
  - Better utilization of the spatial DoF of massive MIMO
  - Enables WB with single-RAT small cell equipments
- Challenges for joint design of small cell wireless backhaul and cell association
  - Interference management
  - Load balancing and fairness considerations
  - Balancing between per-cell throughput and backhaul constraint

Massive MIMO IB-WB (Cont'd)

- A two-tier massive MIMO IB-WB HetNet model
  - Large-scale MIMO MBS with N_T antennas, N_S single-antenna small cells, N_U single-antenna MTs
  - In-band wireless backhaul for small cells and $N_T \gg N_{actives}$
  - Space-frequency resource block sharing and scheduling



N. Wang, E. Hossain, and V. K. Bhargava, "Joint downlink cell association and bandwidth allocation for wireless backhauling in two-tier HetNets with large-scale antenna arrays," *IEEE Transactions on Wireless Communications*, vol. 15, no. 5, pp. 3251-3268, 2016.

Joint CA-WBBA Problem

- Downlink CA under SC-WB constraint
  - Maximizing sum of log-rate subject to small cell wireless backhaul constraints
  - Objective chosen to balance between throughput and fairness

$$
\begin{aligned}
\mathbf{P1}: \ \underset{\beta, \mathbf{X}}{\text{maximize}} \quad & \bar{R}^U(\beta, \mathbf{X}) \\
\text{subject to} \quad & x_{j,k} \in \{0, 1\}, \ \forall (j, k) \in \mathcal{S}_0 \times \mathcal{U}; \\
& \sum_{j \in \mathcal{S}_0} x_{j,k} = 1, \ \forall k \in \mathcal{U}; \\
& 0 \le \beta \le 1; \\
& R_j^U \le C_j^U, \ \forall j \in \mathcal{S}.
\end{aligned}
$$

Relaxation and H-Decomposition

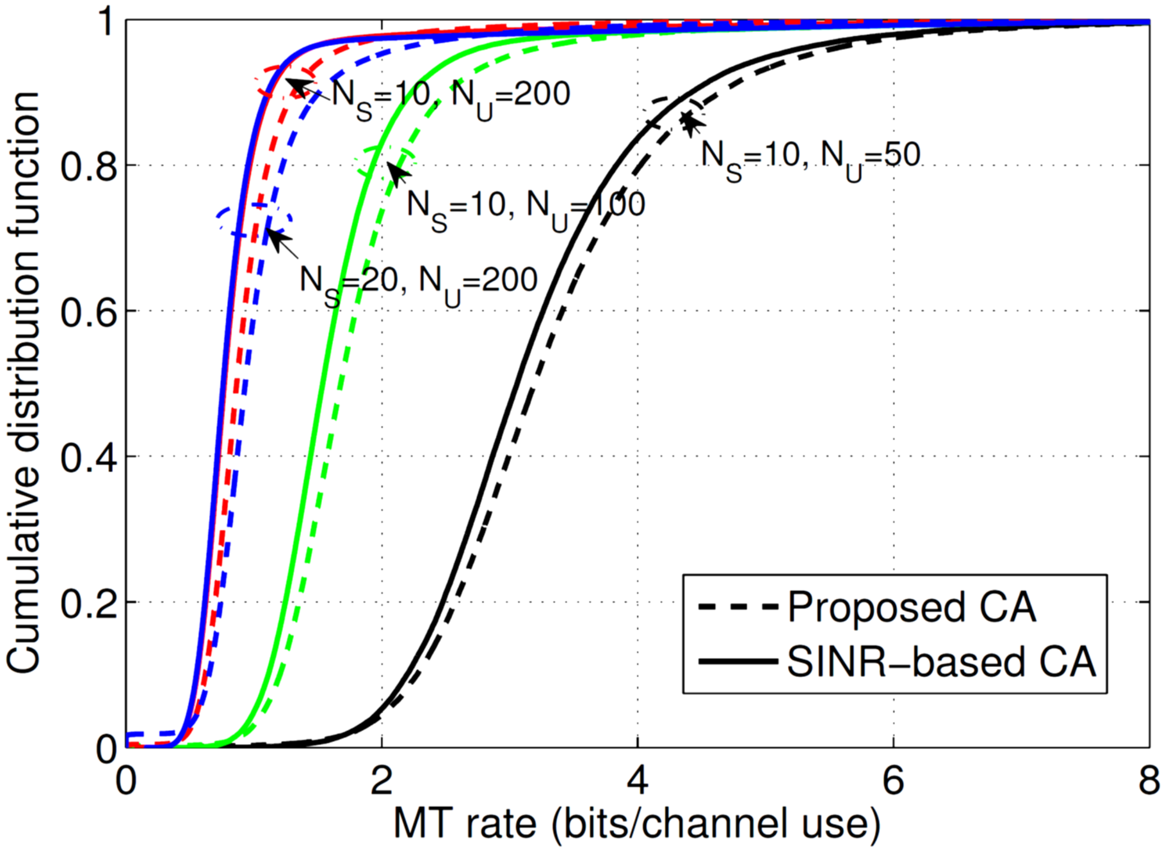
- The solution approach
  - Relax the binary cell association indicators to continuous
  - Hiearachical decomposition:
    Upper level primal decomposition and lower level dual decomposition
  - Distributed iterative algorithm

$$
\begin{aligned}
\mathbf{P1.1}: \ \underset{\mathbf{X}}{\text{maximize}} \quad & \sum_{j \in \mathcal{S}_0} \bar{R}_j^{U'}(\mathbf{X}) \\
\text{subject to} \quad & x_{j,k} \geq 0, \ \forall (j,k) \in \mathcal{S}_0 \times \mathcal{U}; \\
& \sum_{j \in \mathcal{S}_0} x_{j,k} = 1, \ \forall k \in \mathcal{U}, \\
& R_j^U(\mathbf{X}; \beta) - C_j^U(\mathbf{X}; \beta) \leq 0, \forall j \in \mathcal{S},
\end{aligned}
$$

$$
\begin{aligned}
\mathbf{P1.2}: \ \underset{\beta}{\text{maximize}} \quad & N_U \log(1-\beta) + \sum_{j \in \mathcal{S}_0} \bar{R}_j^{U'}(\mathbf{X}^\star) \\
\text{subject to} \quad & 0 \leq \beta \leq 1; \\
& R_j^U(\beta; \mathbf{X}^\star) - C_j^U(\beta; \mathbf{X}^\star) \leq 0, \ j \in \mathcal{S},
\end{aligned}
$$

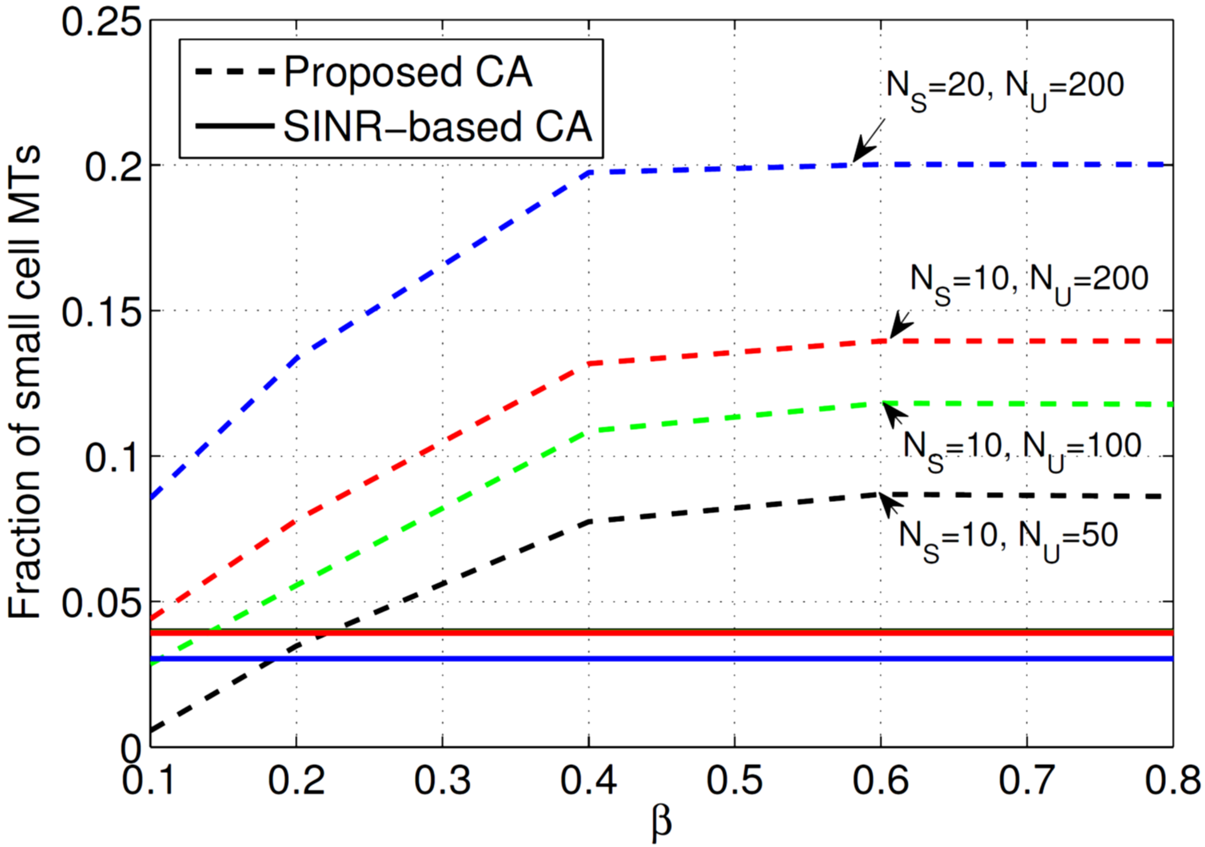
User Rate Distribution

- Empirical CDF of the user rates



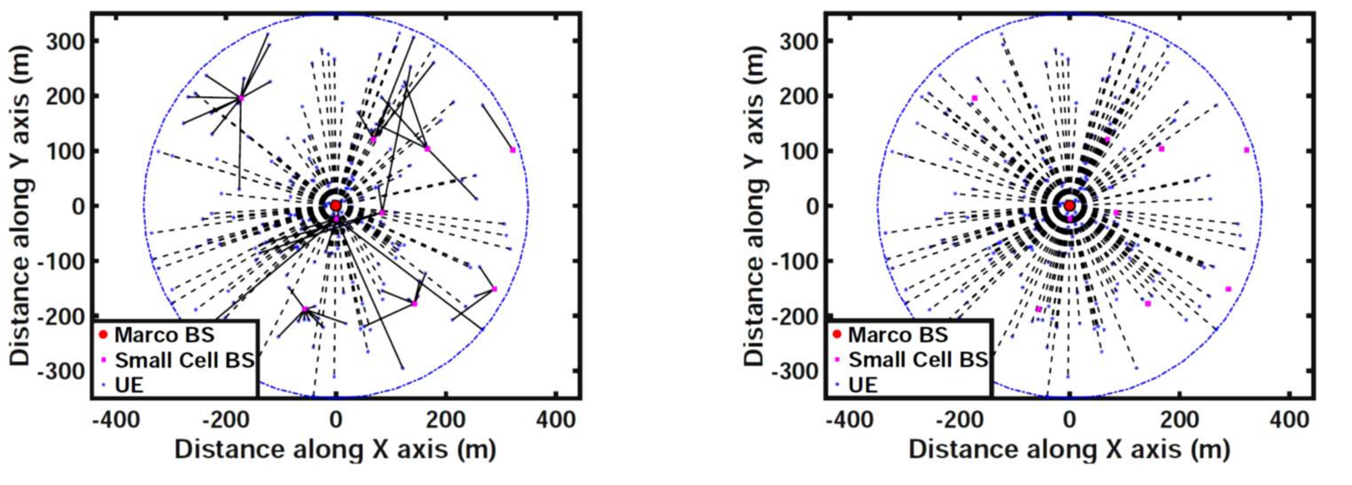
Inter-Tier Load Balancing

- Inter-tier load balancing of the proposed scheme



Sub-6GHz v.s. mmWave

- **Scenario 1:** Random user locations
  - 3.5GHz (sub-6GHz band) and 30GHz (mmWave band)
  - SBSs and users uniformly deployed within MBS coverage

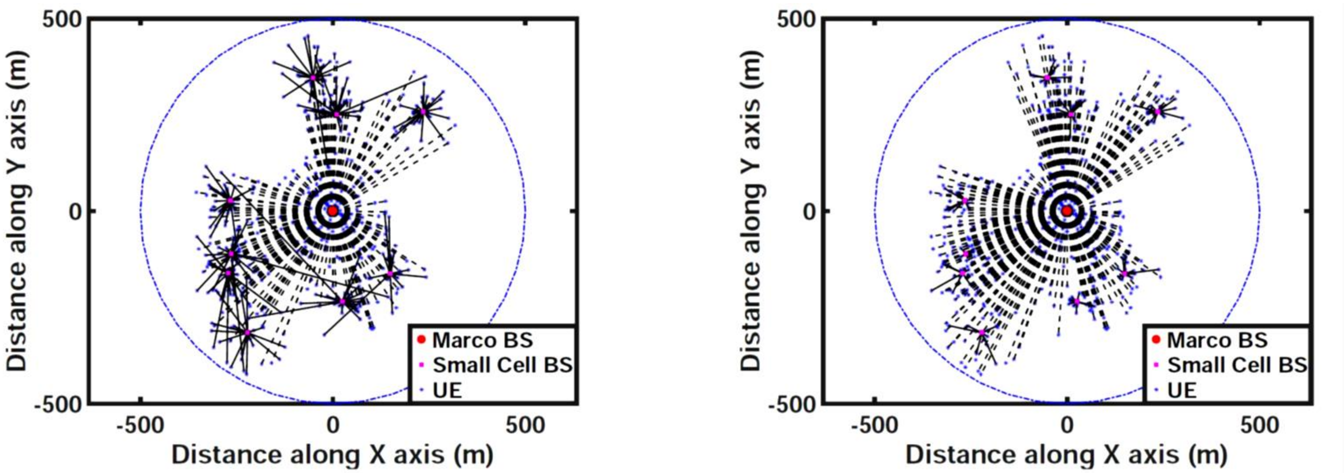


(a) Random scenario in 30 GHz (b) Random scenario in 3.5 GHz

Z. Su, B. Ai, N. Wang, *el. al*, "User association and wireless backhaul bandwidth allocation for 5G heterogeneous networks in the millimeter-wave band," *China Communications*, vol. 15, no. 4, pp. 1-13, 2018.

Sub-6GHz v.s. mmWave (Cont'd)

- **Scenario 2:** Hotspot user locations
  - 3.5GHz (sub-6GHz band) and 30GHz (mmWave band)
  - SBSs uniformly deployed within MBS coverage
  - Users distribution around hotspots (SBSs)



(c) Hotspot scenario in 30 GHz (d) Hotspot scenario in 3.5 GHz

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How to Reduce Analog RF Cost?

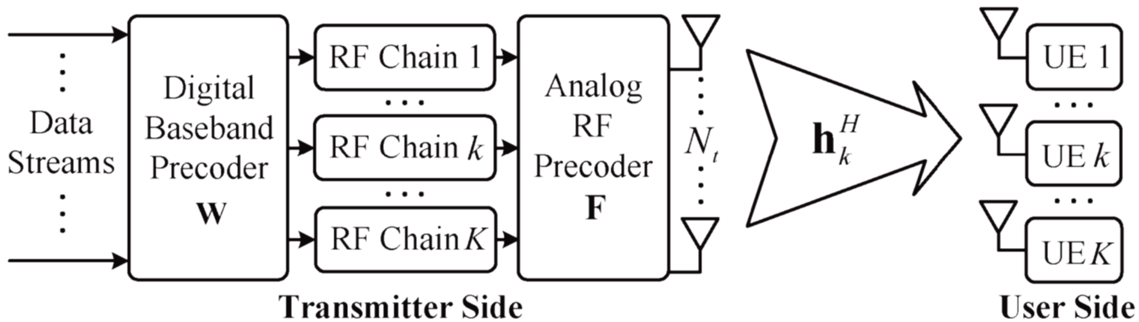
- Some facts
  - Cost of digital processing drops much faster than the RF
  - RF chains (LNA, PA, converter, ADC, DAC) are particularly expensive and energy consuming
  - Antennas are typically less expensive
- Some ideas
  - Reduce the number of RF chains: Limited RF chains
  - Use low-end RF hardware
    Performance analysis with low-end RF hardware
    Novel designs with low-end RF hardware

1 Limited RF Chain Constraint

- How to design a massive MIMO system if the number of RF chains is limited?
  - Hybrid precoding instead of pure digital precoding

$$y_k = \mathbf{h}_k^H \mathbf{F} \mathbf{W} \mathbf{s} + n_k \qquad \mathbf{F}_{i,j} = \frac{1}{\sqrt{N_t}} e^{j\varphi_{i,j}}$$

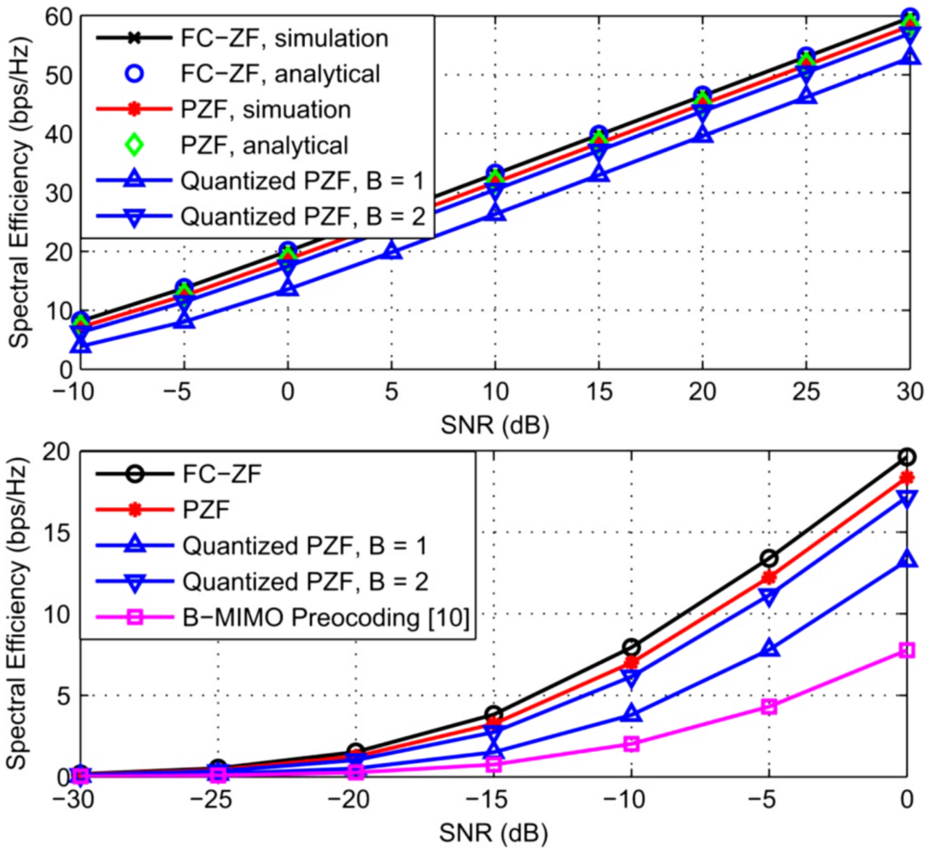
$$\mathbf{W} = \mathbf{H}_{eq}^H \left(\mathbf{H}_{eq} \mathbf{H}_{eq}^H \right)^{-1} \mathbf{\Lambda}$$



L. Liang, W. Xu, and X. Dong, "Low-complexity hybrid precoding in massive multiuser MIMO systems," *IEEE Wireless Communications Letters*, vol. 3, no. 6, pp. 653-656, 2014.

Performance of P-ZF

- Using P-ZF in Rayleigh fading and mmWave



[2] Hybrid Precoding for PHY Sec

- Extension to downlink hybrid precoding for joint information and AN transmissions

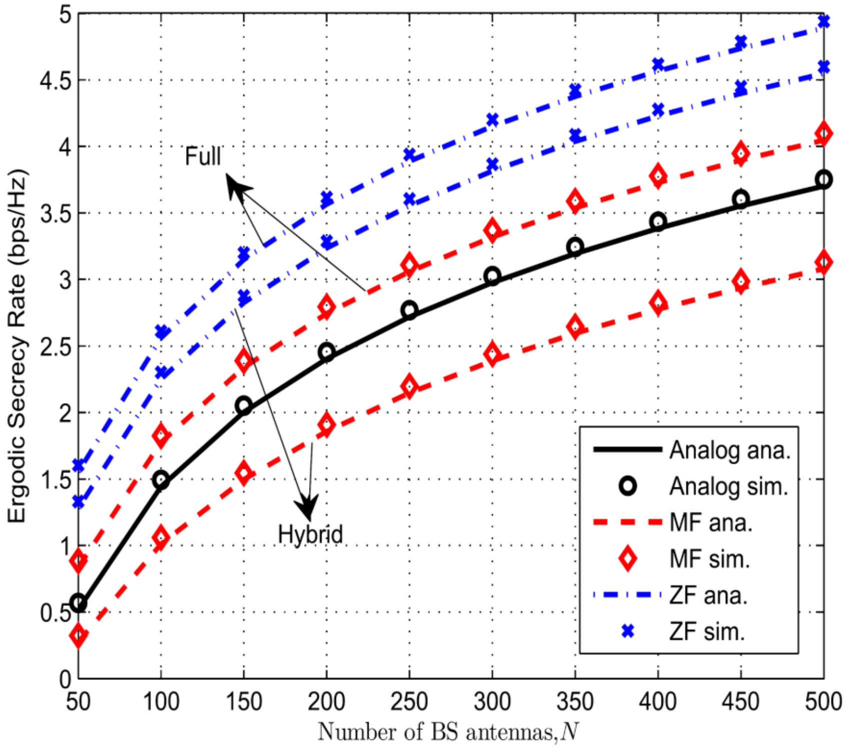
$$y_k = \mathbf{g}_k^H \mathbf{FWs} + \mathbf{g}_k^H \mathbf{AVz} + n_k$$
$$\mathbf{y}_e = \mathbf{G}_E^H \mathbf{FWs} + \mathbf{G}_E^H \mathbf{AVz} + \mathbf{n}_e$$

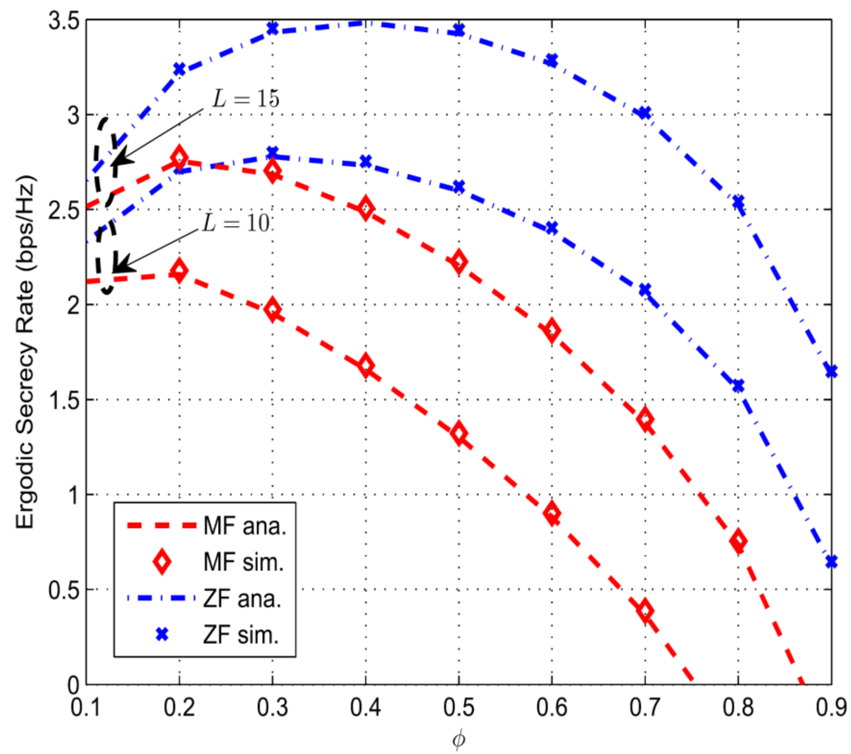
  - P-ZF, P-MF, and phase-only conjugate data precoders
  - Phase-only iterative null-space AN precoder
  - Impacts of antenna array size, number of RF chains, and power allocation between data and AN examined

J. Zhu, W. Xu, and N. Wang, "Secure massive MIMO systems with limited RF chains," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 6, pp. 5456-5460, 2017.

Secure H-Precoding Evaluation

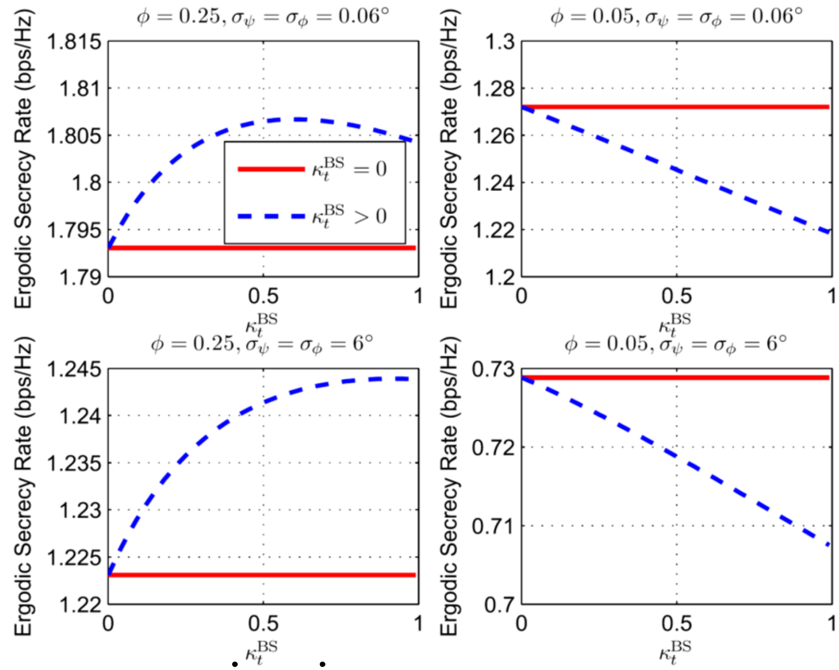
- Evaluation of P-ZF, P-MF, and analog only precoders for secure massive MIMO transmission





3 Impact of Hardware Impairments

- Hardware impairments in massive MIMO
  - Multiplicative phase noise
    Additive distortion noise
    Amplified receiver noise

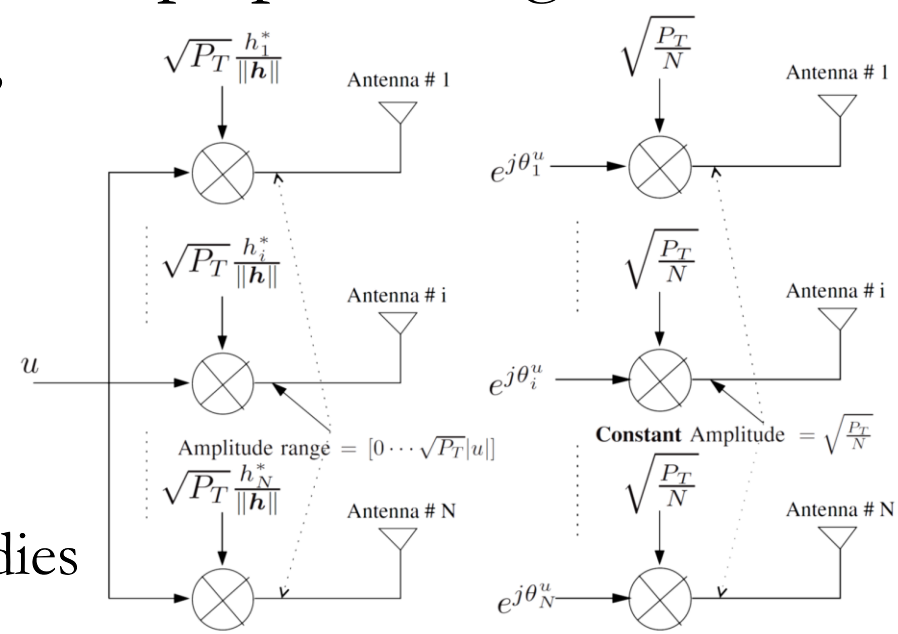


- Secure transmission with AN injection
  - Additive distortion noise at the BS may be beneficial
  - Other HWIs essentially have a negative impact
  - Proposed a generalized NS design to improve secrecy

J. Zhu, D. W.-K. Ng, N. Wang, *et. al*, "Analysis and design of secure massive MIMO systems in the presence of hardware impairments," *IEEE Transactions on Wireless Communications*, vol. 16, no. 3, pp. 2001-2016, 2017.

4 Per-Antenna CE Precoding

- Use low-cost PA to achieve high performance?
- Per-antenna constant envelope precoding
  - Constant operation point, zero dynamic range requirement
  - Simple receiver structure
  - Non-linear precoding, high complexity, lack of information theoretic studies



(a) MRT (b) CE

N. Wang, J. Zhu, W. Xu, *et. al*, "A Note on per-antenna constant envelope precoding for large-scale multi-user MIMO systems," *IEEE Transactions on Wireless Communications*, manuscript under preparation, 2018.

Per-Antenna CE Precoding (Cont'd)

- Some observations with PACE precoding
  - Received signal region is a doughnut channel for MISO
  - Received signal regions for MU-MIMO are correlated between users and difficult to characterize as in MISO
  - MU-MIMO PACE precoding needs to be characterized statistically by outage probability
  - For secure transmission design, a phase noise channel model is more appropriate (gives non-trivial bounds) than the AWGN model, especially for eavesdropping channel

J. Zhu, N. Wang, and V. K. Bhargava "Per-antenna constant envelope precoding for secure transmission in large-scale MISO systems," in *Proc. IEEE/CIC ICCC 2015*, Shenzhen, China, Dec. 2015.

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Summary

- 5G is coming, and massive MIMO is the key enabling technology for early stage 5G networks
- Cost is the major concern for commercial implementations of massive MIMO
- Two cost-effective technical approaches
- Proposed a massive MIMO enabled wireless backhaul architecture for 5G HetNets and UDN
- Design of massive MIMO with lower cost: Limited RF chains v.s. low-cost hardware

Acknowledgement

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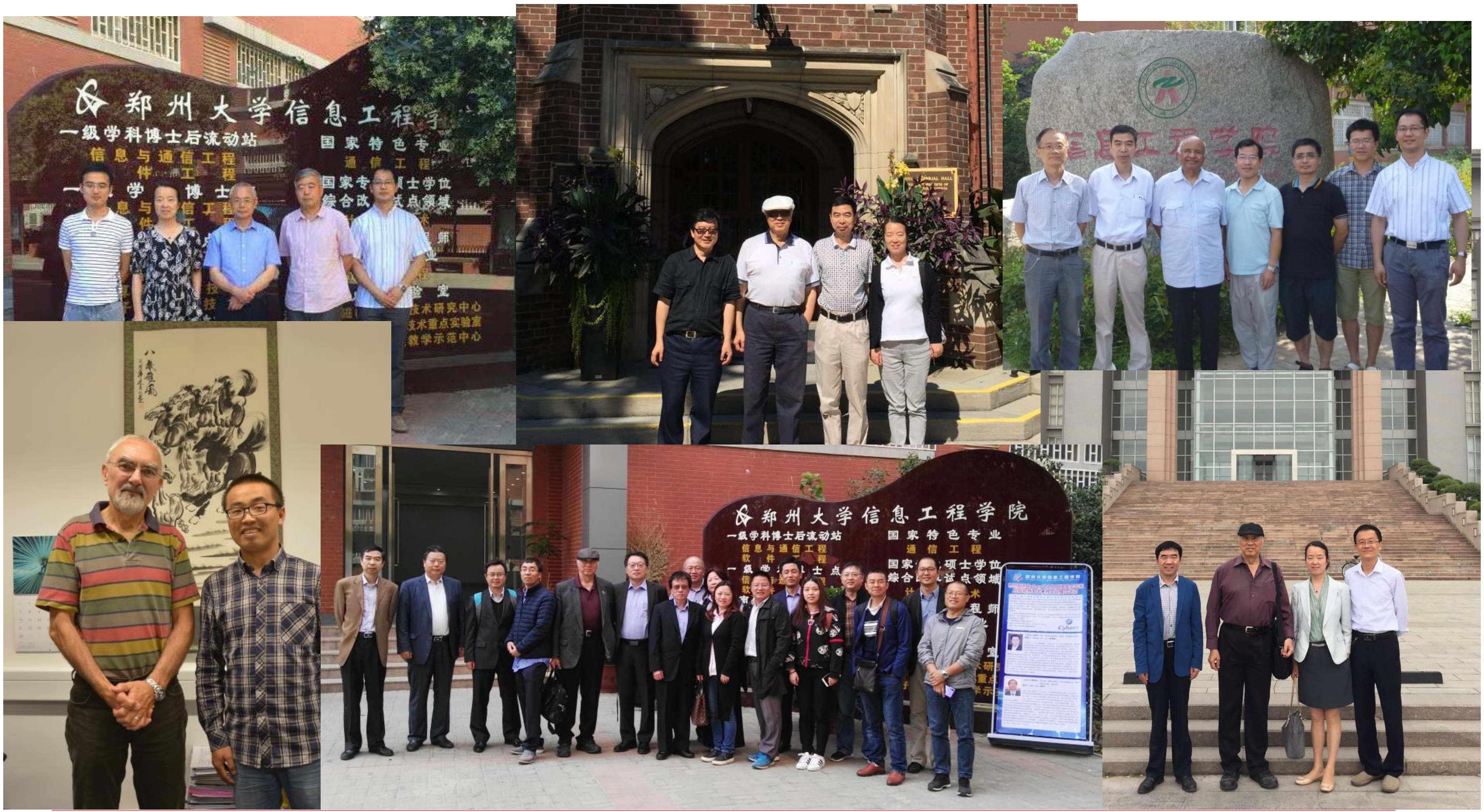
- **ZTE Industry-University Collaborative R&D Project**

Welcome to Zhengzhou University!



Thank You!

Q&A