Ultra Wideband Communications based on Massive MIMO and Multi-mode Antennas Suitable for Mobile Handheld Devices

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100 Gps wireless access

Fiber Optic Internet Access

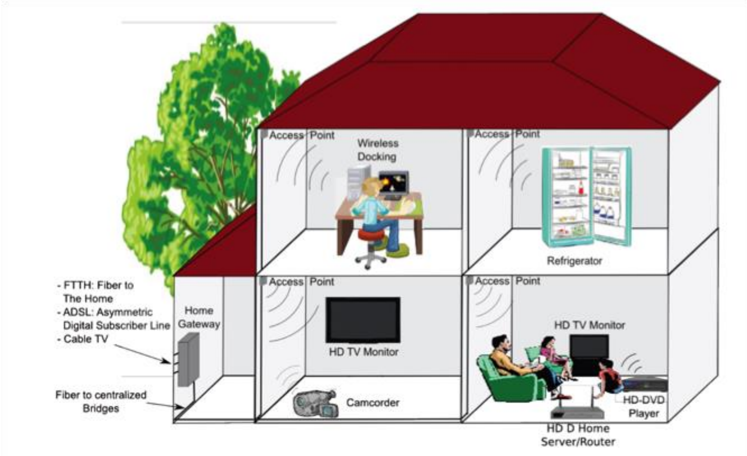
- 100 Gbit/s ethernet
- IEEE 802.3ba-2010

Wireless Bottleneck

- Access point → Device
- IEEE 802.11n → 600 Mbit/s
- IEEE 802.11ac,d → 7 Gbit/s

Future Access Concepts

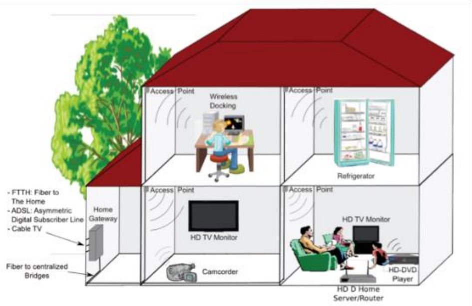
- Free-space optical links
- mm-wave (>60 GHz) UWB
- Massive MIMO



100 Gps wireless access

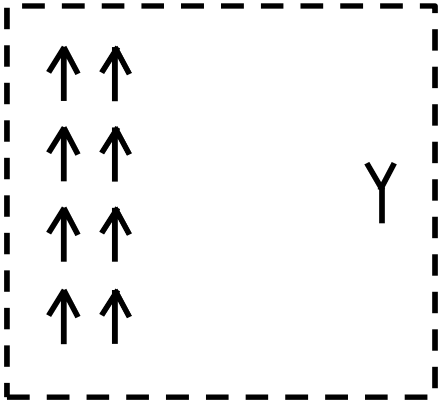
EU-UWB Spectral Mask

- 6 GHz – 8.5 GHz (PSD < -42dBm/MHz)
- Good progagation conditions indoors
- Mature technology



Bottlenecks

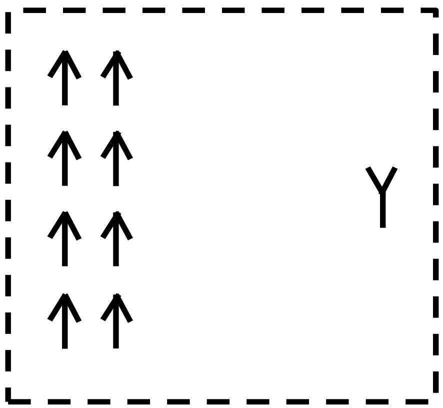
- Ultra high spectral efficiency 100 Gbps → 40 bps/Hz
- Manageble computational complexity
- $\lambda(f_c$=7.25GHz)≈4cm → size of antenna element



UWB Massive MIMO

- UWB antennas
- Massive multi antenna system on access point
- Multi antenna system on mobile terminal

Massive MIMO Antenna Elements



Many Antennas per Access Point

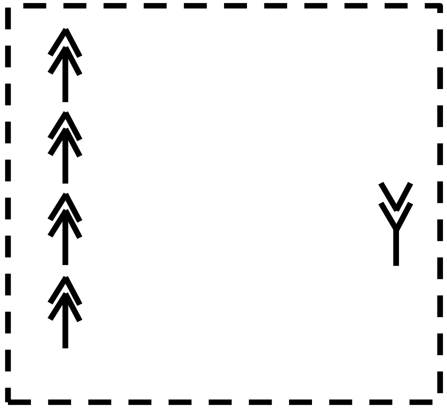
- 100 … 1000 antennas
- Low mutual coupling s_{ij} < -20 dB
- Low envelope correlation

Typical Antenna Concepts

- Crossed dipoles
- Dual mode patch antennas
- Large size of array

***Compact* Multi-Mode Approach**

- Multiple modes per element
- Compact antenna array



Compact Massive Multi-Antenna System

DFG SPP 1655

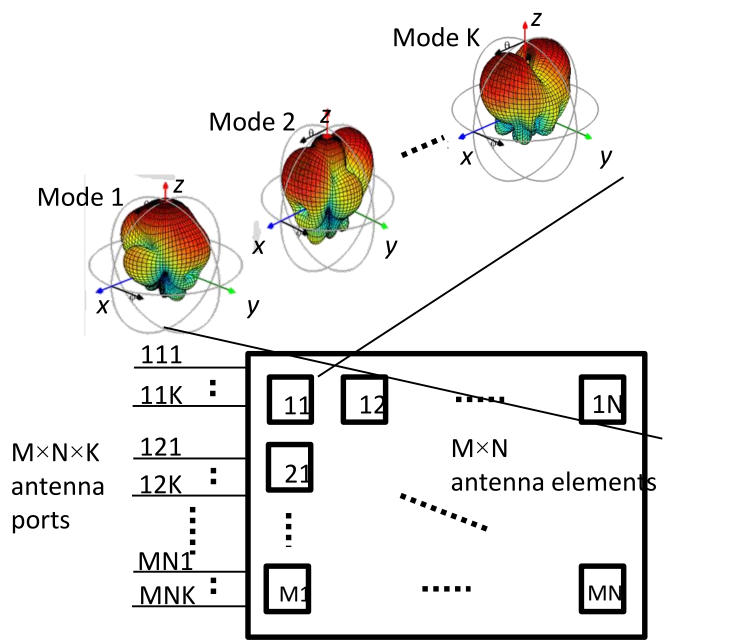
- Priority Project of Germany Research Foundation

DFG SPP 1655 – Wireless 100 Gb/s and beyond

- Indoors to support 100+ Gbit/s wireless internet access
- requires
  - Ultra wide bandwidth
  - Massive MIMO

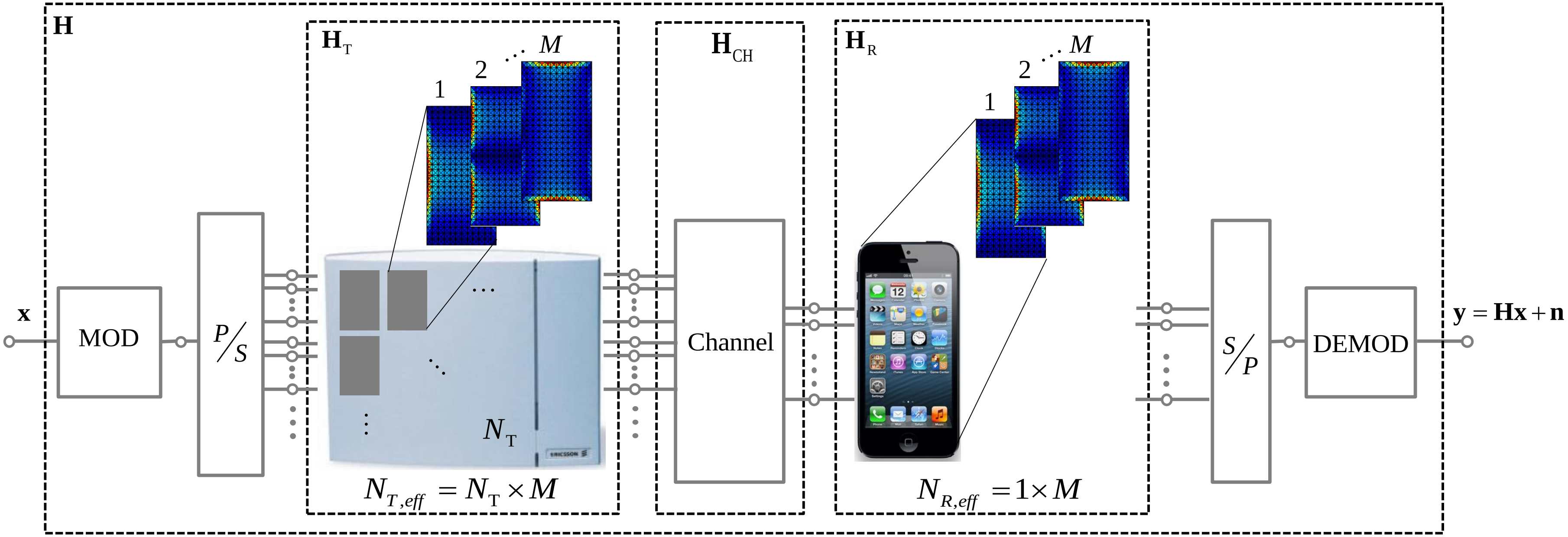
Compact antenna concept

- Based on multi-mode elements
- $N_{ports} = k_{Elements} \times m_{Modes}$



Multi Mode Multi Element Antenna (MEA) M^3EA

System Concept



- Access Point: Massive Multi Element Antenna using Multi-Mode Elements featuring orthogonal patterns
- Mobile Terminal: Multi Antenna System based on orthogonal chassis modes

P.A. Hoeher, N. Doose, „A massive MIMO terminal concept based on small-size multi-mode antennas," Trans. Emerging Telecommun. Techn., Mar. 2015.

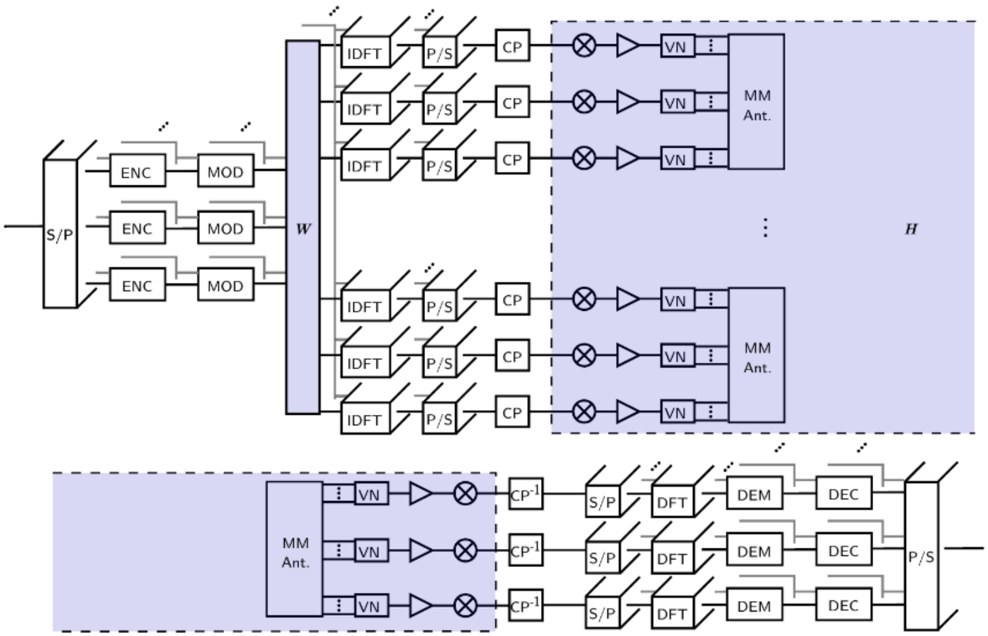
System Concept

System Advantages

- Inherent orthogonalization, reduced spatial correlation
- Manageable computational complexity
- High flexibility w.r.t. adaptive multi-stream baseband processing

System Concept

- Baseband system concept and configuration[*]
- Joint beamforming and EIRP control
- Low complexity receiver design



- [*] **N.Doose, P.A. Hoeher**, „On EIRP control in downlink precoding massive MIMO arrays,“ in Proc. ITG Workshop on Smart Antennas, accepted for publication, Mar. 2016.

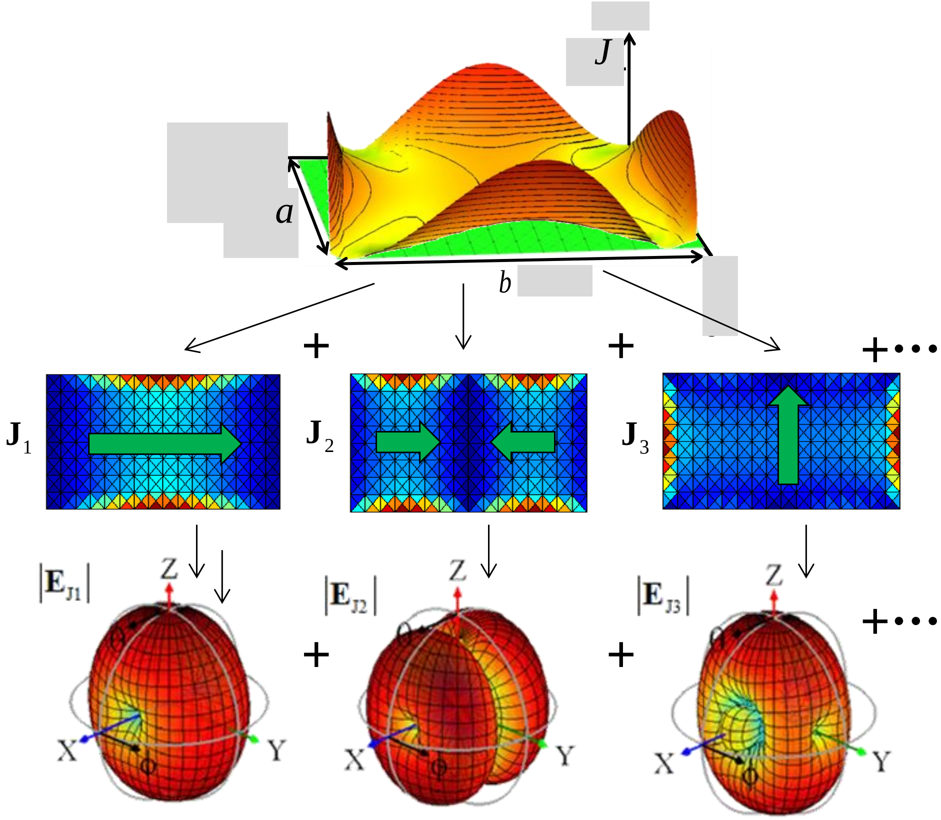
Theory of Characteristic Modes

Surface Current Distribution

- Antenna radiation is based on the current density distribution of the antenna.
- The surface current density on any finite body can be decomposed into a set of Characteristic Modes*:

$$\mathbf{J} = \sum_n a_n \mathbf{J}_n$$

- Char. Modes can be excited selectively by multiple antenna ports!



* * R. F. Harrington and J. R. Mautz, "Theory of characteristic modes for conducting bodies," IEEE Trans. Antennas Propagat., vol. 19, no. 5, pp. 622–628, Sept. 1971.

Theory of Characteristic Modes

Properties of Char. Modes

- Orthogonality

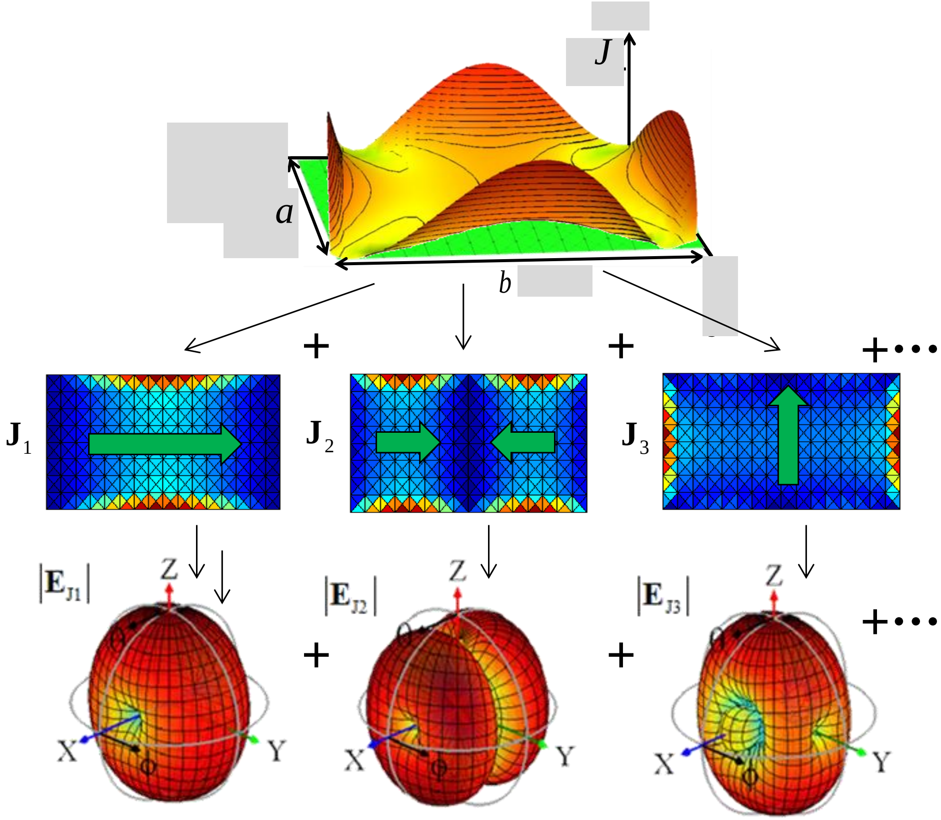
$$\left\langle \mathbf{J}_m^*, \mathbf{Z}\mathbf{J}_n \right\rangle = \iint_A \mathbf{J}_m^* \cdot \mathbf{Z}\mathbf{J}_n dA = \left(1 + j\lambda_n\right)\delta_{mn}$$

$$\text{where } \delta_{mn} = \begin{cases} 0 \; if \;\; m \neq n \\ 1 \; if \;\; m = n \end{cases}$$

$$\mathbf{J} = \sum_n a_n \mathbf{J}_n$$

$$\mathbf{E} = \mathrm{L}(\mathbf{J})$$

$$\mathbf{E} = \sum_n a_n \mathbf{E}_n$$



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Theory of Characteristic Modes

Eigenvalue & Modal Significance

- Char. Modes:

$$\mathbf{J} = \sum_n a_n \mathbf{J}_n = \sum_n \underbrace{\frac{1}{(1+j\lambda_n)}}_{MS} V_n^i \mathbf{J}_n$$

MS: Modale Significanz

Excitation (V_n^i)

- Modal Power:

$$P = P_{rad} + jP_{reac}$$

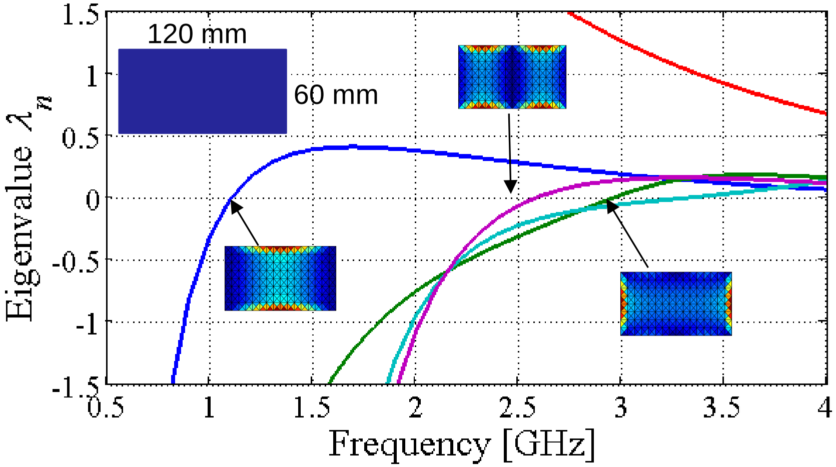
$$= \sum_{n=1}^{N} |a_n|^2 (1+j\lambda_n)$$

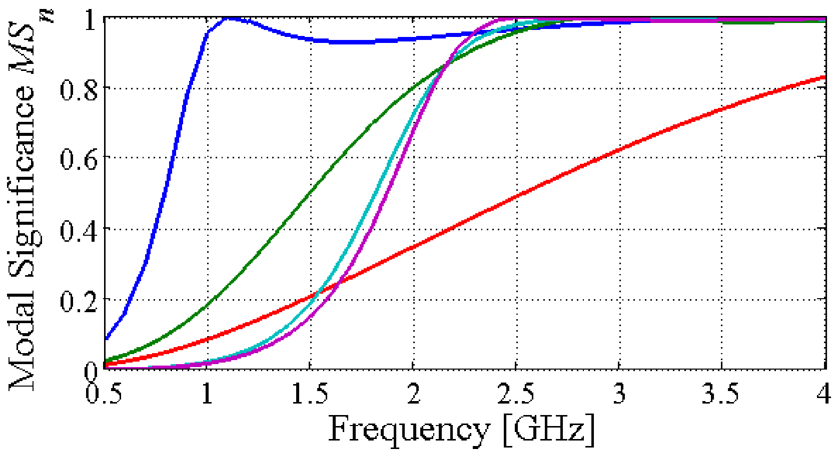
$$= \sum_{n=1}^{N} MS_n^{\ 2} |V_n|^2 (1+j\lambda_n)$$

$MS_n^{\ 2}$: Should be high

$|V_n|^2$: Excitation

λ_n: Should be small





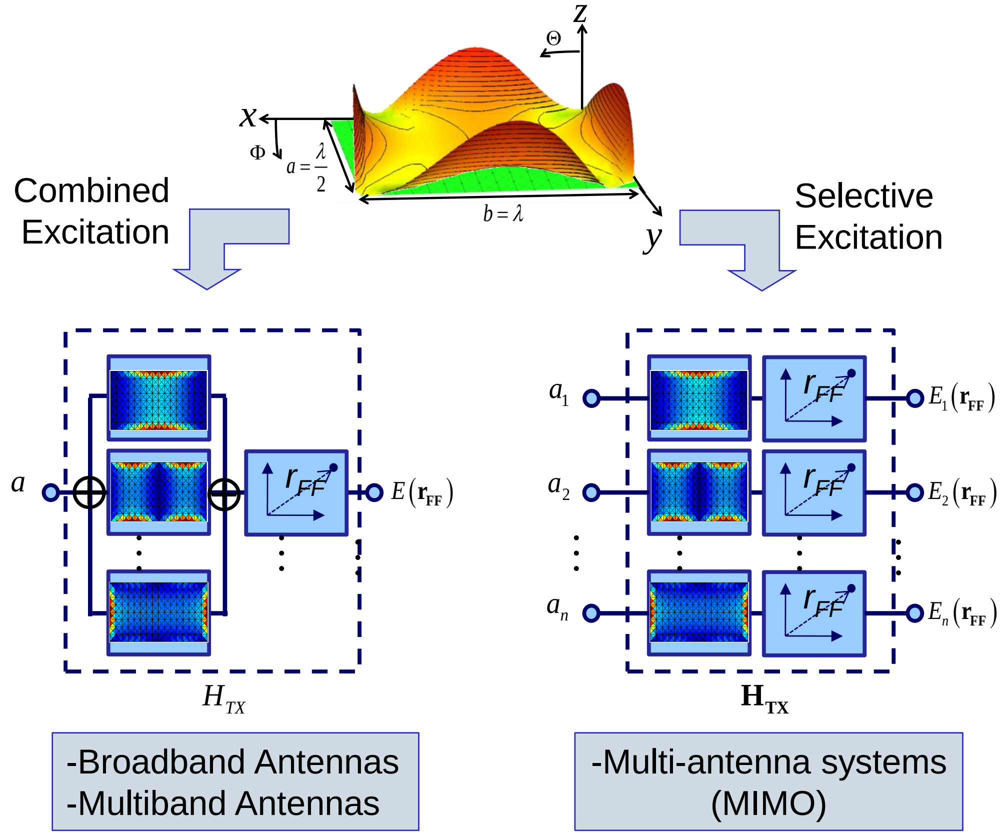
Theory of Characteristic Modes

Combined Excitation of Modes

- Excitation of multiple modes
- by capacitive couplers
  - Multiband antennas
  - Broadband antennas

Selective Excitation of Modes

- Excitation of different modes per antenna port
- by inductive couplers
  - Multi-Antenna Systems

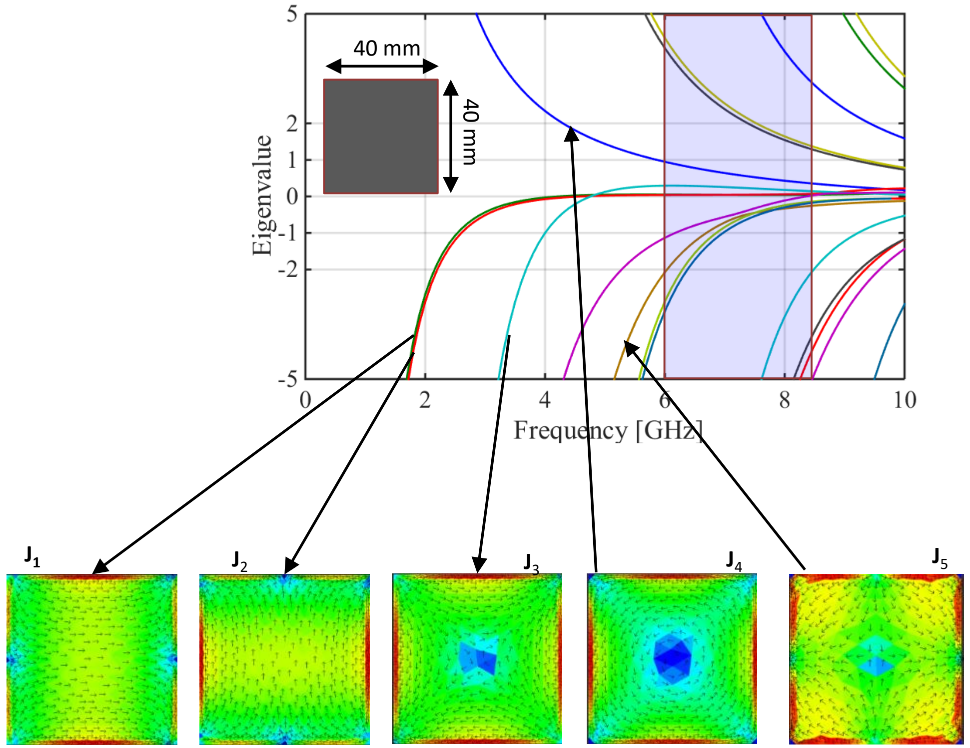


- Martens, R. and Manteuffel, D. , "Systematic Design Method of a Mobile Multiple Antenna System Using the Theory of Characteristic Modes," IET MAP, Vol 8, Issue 12, Sept. 2014, pp. 887 – 893.

Compact Massive Multi-Antenna System

Char. Modes of antenna element

- 6 < *f*[GHz] < 8.5
- Many modes have low Eigenvalues
- Excite these modes selectively
- By decoupled antenna ports

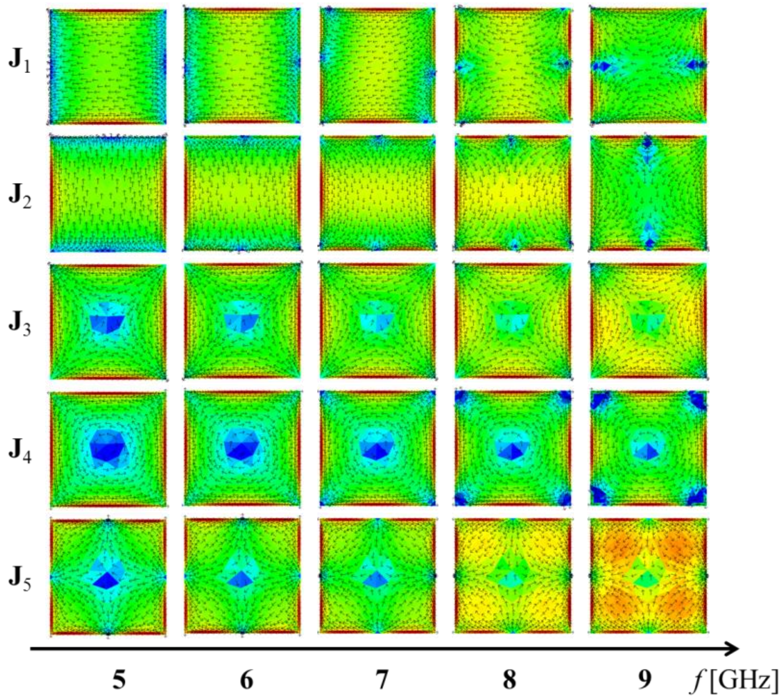


D. Manteuffel and R. Martens, "Compact Multimode Multielement Antenna for Indoor UWB Massive MIMO," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 7, pp. 2689-2697, July 2016

Compact Massive Multi-Antenna System

Frequency Dependence

- Modal current distribution varies with frequency
- This needs to be taken into account for the excitation concept
- Identify local (hot) spots that are almost stable throughout the frequency range and unique to a certain mode or set of modes
- ► Design local exciters to be placed into these (hot) spots



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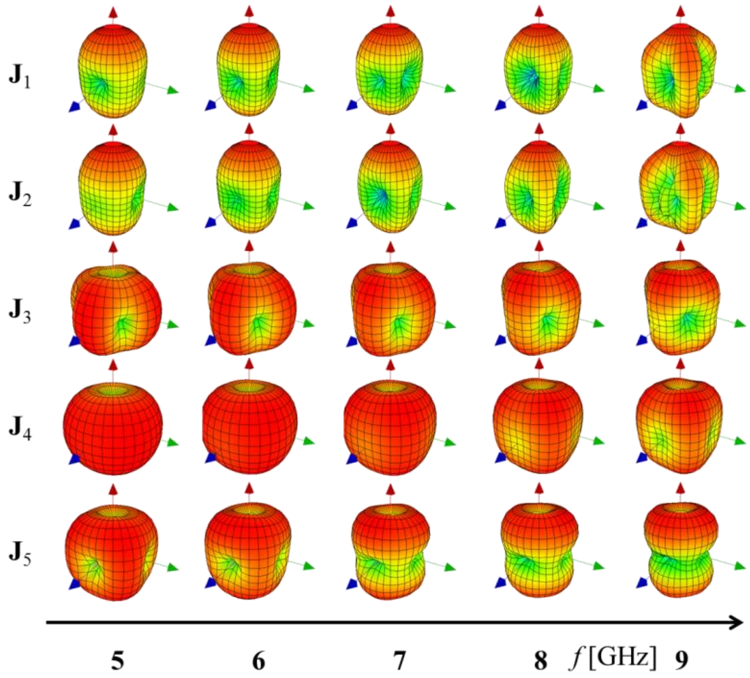
Compact Massive Multi-Antenna System

Frequency Dependence

- Modal current distribution varies with frequency
- The modal pattern varies with frequency as well
- This is not necessarily a problem for a MIMO system
- But it has to be taken into account for the beamforming depending on
  - the entire band is cut into narrower channels
  - or the entire bandwidth is used



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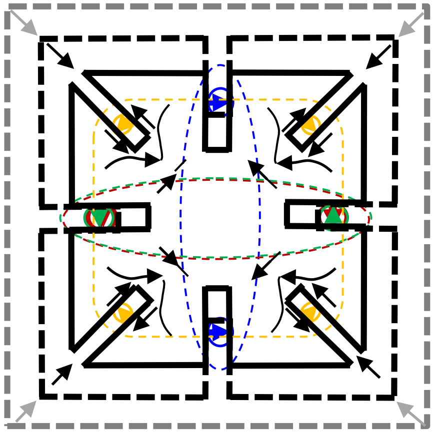
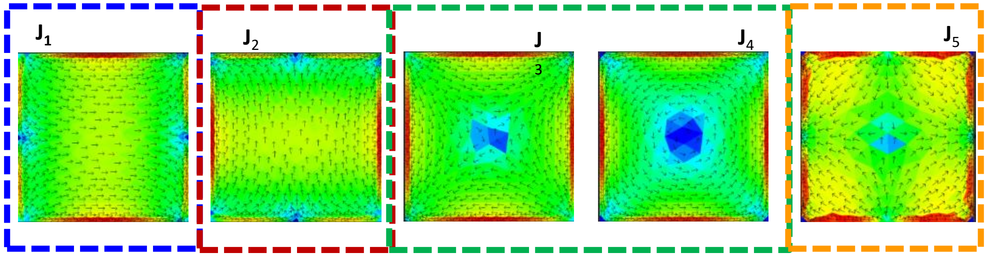


Excitation Concept

- Realize excitation of specific modes
- Modify structure to support selective excitations
- Slot-gap excitation of desired mode
- Excite 4 different mode combinations



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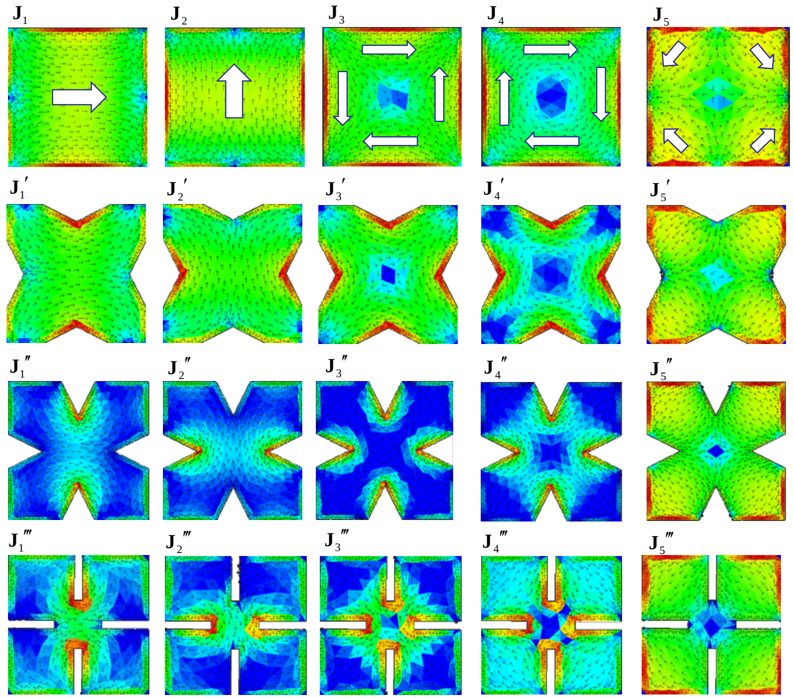
Compact Massive Multi-Antenna System

Evolution of Antenna Element

- Gradual modification of initial quadratic plate towards slotted element for placement of gap ports
  - Modal current distribution changes as geometry evolves
  - Individual local (hot) spots remain similar for the new modes
  - Location around spots allow for gap source excitation



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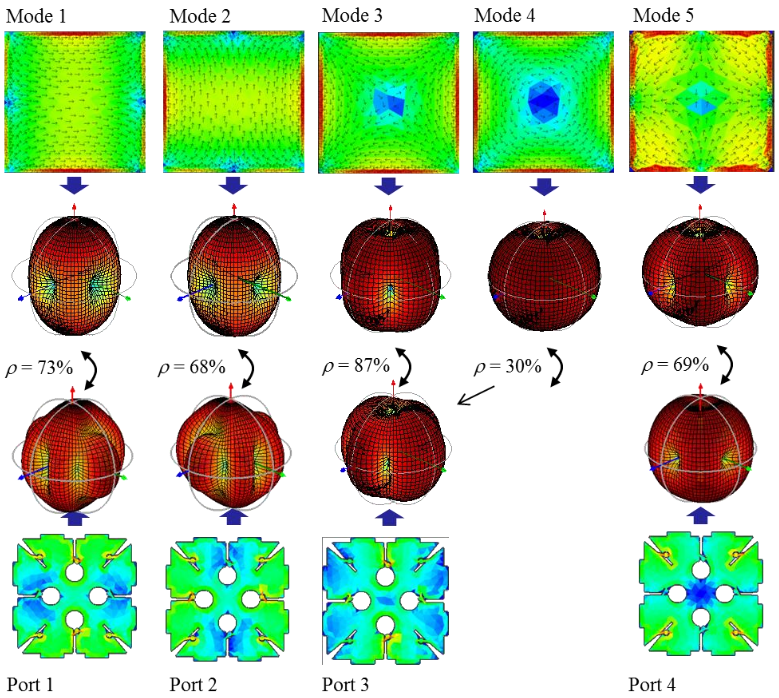
Compact Massive Multi-Antenna System

Scientific Exercise

- How similar are the patterns excited on the modified element to the modal patterns of the inital quadratic plate
- Calculate the cross-correlation of the modal patterns of the quadratic plate and the patterns excited by the four set of ports on slotted plate

- They are still quite similar!
- Because most of the currents arround the slot weakly contributes to radiation



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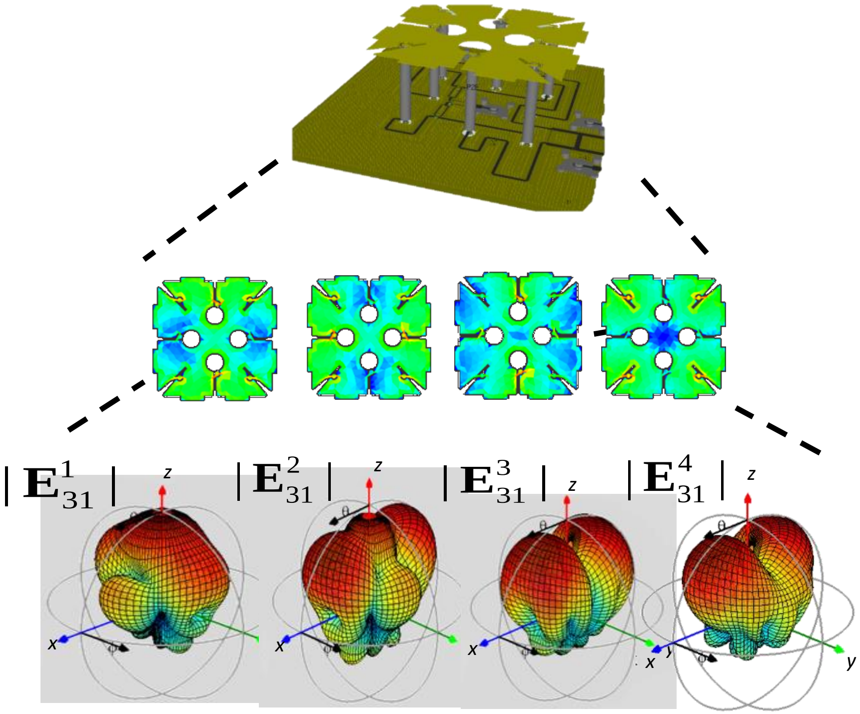
Compact Massive Multi-Antenna System

Multi Mode Element

- Quadratic plate
- Open-slot coupling elements
- Microstrip feed network on backside of reflector plate
- 4 ports for excitation of different sets of modes

Performance

- $|s_{ii}| < -10$ dB
- $|s_{ji}| < -20$ dB
- TARC ≥ 10 dB
- $|\rho_{ji}| \geq 20$ dB



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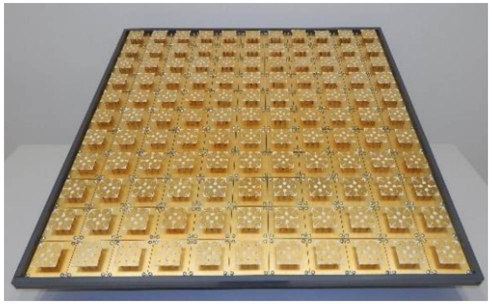
Compact Massive Multi-Antenna System

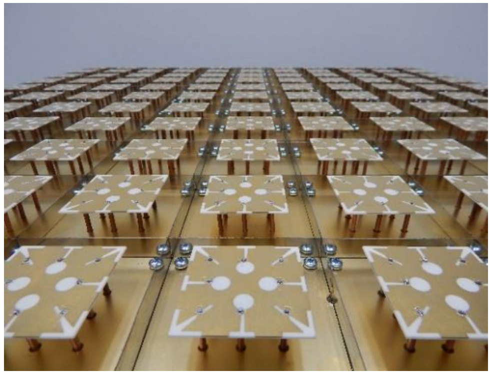
Massive Multi Mode Multi Element Antenna

- 11 × 11 physical elements
- 4 ports per physical element
- ▸ 484 effective antenna ports

Size of antenna

- Multi-Mode array: 230 λ^2
- Crossed dipoles: 498 λ^2
- ▸ Size reduction: 54 %





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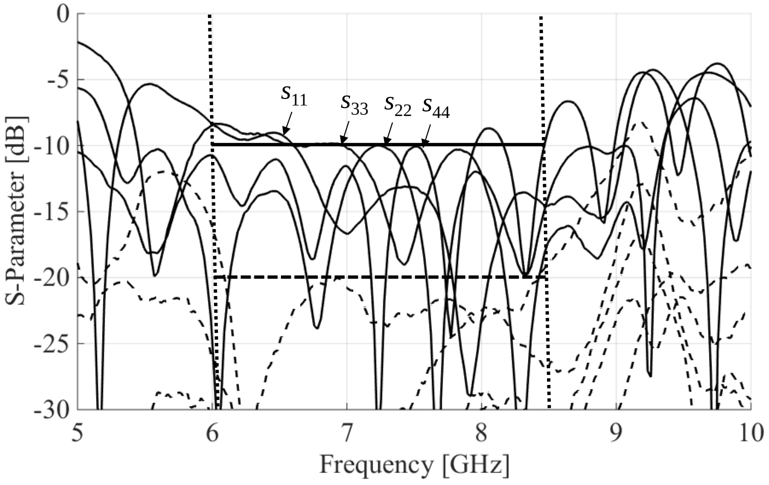
Compact Massive Multi-Antenna System

S-Parameters of Antenna

- S_{ii} < -10 dB in almost entire frequency band



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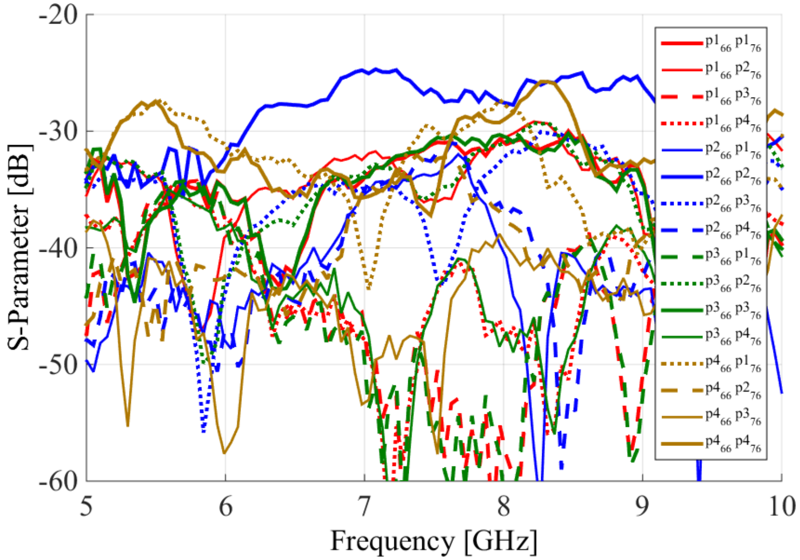
Compact Massive Multi-Antenna System

S-Parameters of Antenna

- S_{ii} < -10 dB in almost entire frequency band
- S_{ji} < -20 dB in entire frequency band



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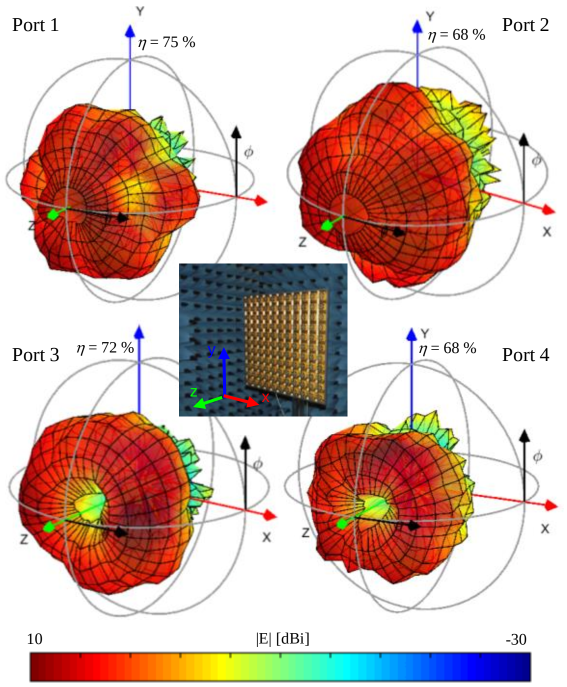
Compact Massive Multi-Antenna System

Measured Radiation Pattern

- Center element measured
- f = 7.25 GHz
- 4 ports
- Antenna efficiency $\eta_{1\text{-}4} \cong 70\ \%$



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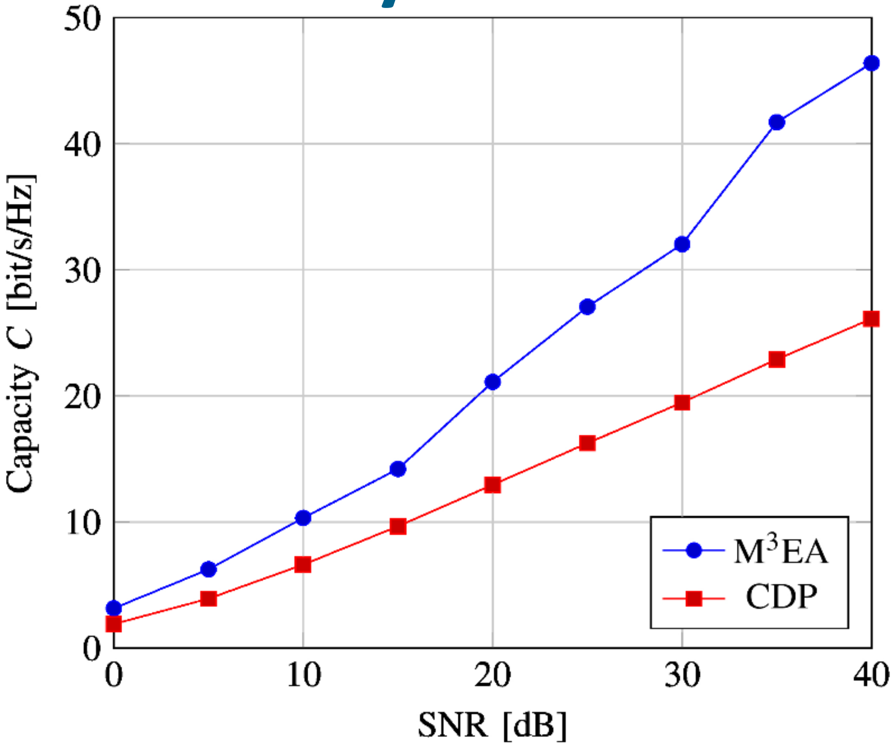
Compact Massive Multi-Antenna System

Capacity

- Winner 2 channel model
- Upper limit of capacity
- Comparison of
  - crossed dipole system (CDP)
  - Multi Mode System (M^3EA)
- Same physical size of Antenna system
- 4 Antennas on the mobile
- ▶ M^3EA outperforms CDP



• **[12] D. Manteuffel, N. Doose, P.A. Hoeher**, "Evaluation of a compact antenna concept for UWB massive MIMO," accepted for publication, *GeMiC 2016*