Spatially Oversampled Demultiplexing in mmWave LoS MIMO

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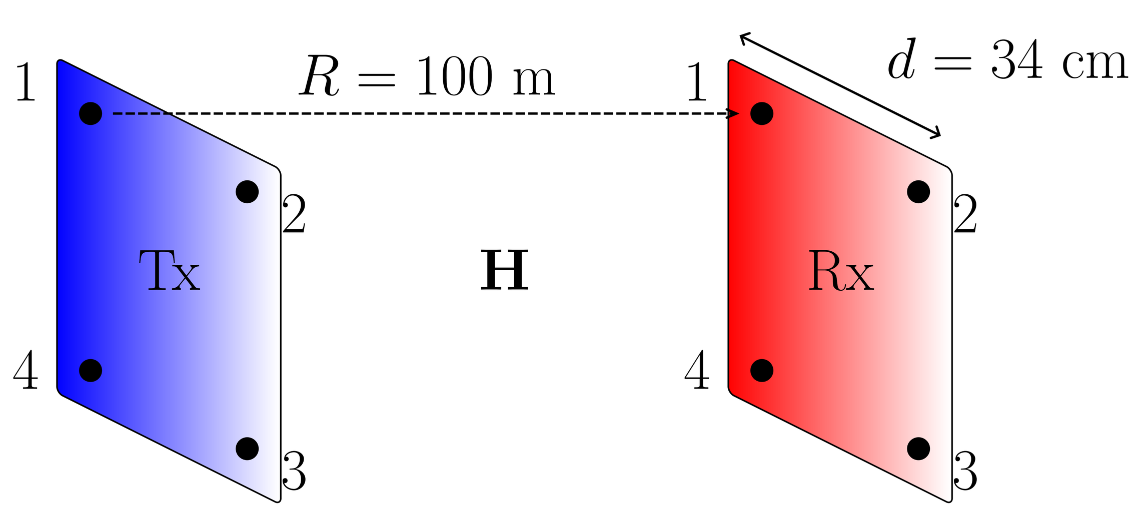
The potential of LoS MIMO

- Spatial degrees of freedom $\sim (A_t A_r)/(\lambda R)^2 \sim f_c^2$ (fixed form factor) [1]
  A_t, A_r – transmit and receive antenna apertures
- Available bandwidth $\sim f_c$
- Data rates $\sim f_c^3$ – strong incentive to push up carrier frequency to mmWave

Example: 4×4 MIMO at 130GHz



→ Channel for ideally aligned LoS MIMO system

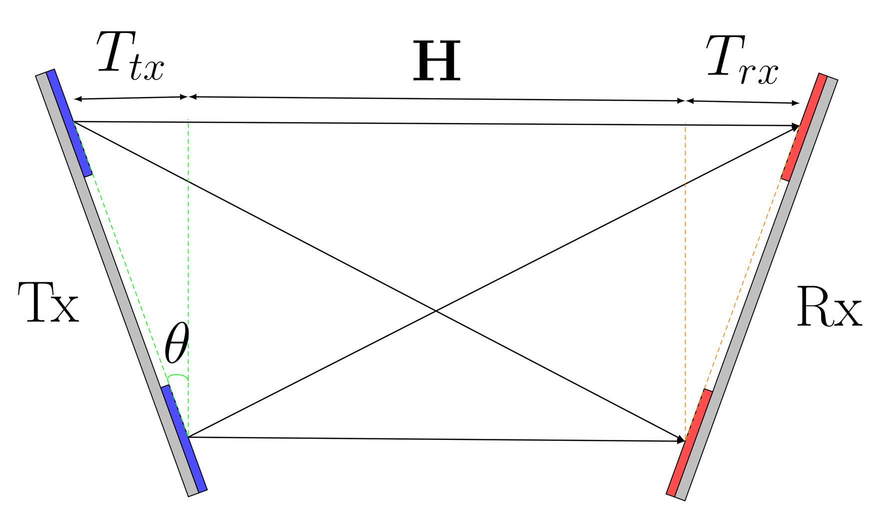
$$\mathbf{H} = \begin{bmatrix} 1 & e^{-j\phi} & e^{-2j\phi} & e^{-j\phi} \\ e^{-j\phi} & 1 & e^{-j\phi} & e^{-2j\phi} \\ e^{-2j\phi} & e^{-j\phi} & 1 & e^{-j\phi} \\ e^{-j\phi} & e^{-2j\phi} & e^{-j\phi} & 1 \end{bmatrix}, \phi = \pi d^2/\lambda R$$

$\mathbf{H}$ is invertible, if $d = \sqrt{R\lambda/2}$ (34 cm at 130 GHz)

→ Achievable data rates > 100 Gbps
$20 \times 4 \times 2 =$ 160 Gbps (20 GBaud, QPSK)

Spatial demux at 10s of GBaud: How?

- Simple approach: invert the channel $\mathbf{H}$
- Vulnerable to even small misalignments



- Even a small $\theta(5^\circ)$ introduce 2 channel symbol delay (T_{tx}) at 20 GHz symbol rate $\left(\frac{d\tan(\theta)}{TC} \approx 2\right)$
- Channel becomes frequency selective [2]

$$\begin{bmatrix} \mathbf{y}_K \\ \mathbf{y}_{K-1} \\ \vdots \\ \mathbf{y}_{K-W+1} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_0 & \cdots & \mathbf{H}_{L-1} & \cdots & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{H}_0 & \cdots & \mathbf{H}_{L-1} & \cdots & \mathbf{0} \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{H}_0 & \cdots & \mathbf{H}_{L-1} \end{bmatrix} \begin{bmatrix} \mathbf{x}_K \\ \mathbf{x}_{K-1} \\ \vdots \\ \mathbf{x}_{K-L-W+1} \end{bmatrix}$$

Conventional DSP architecture ⇒ performance floor

- Symbol rate FIR space-time equalizer → performance floor
- Temporal oversampling out of the question at 20 GBaud

Prior analog approach

- Digitally programmable analog delays – introduce artificial analog delays to mimic the ideal channel

Our observation

- Channel can be inverted with appropriate spatial oversampling
- FIR space-time equalizers with symbol rate sampling
- Small number of taps → both fully digital and hybrid implementations become possible

Spatially oversampled reception

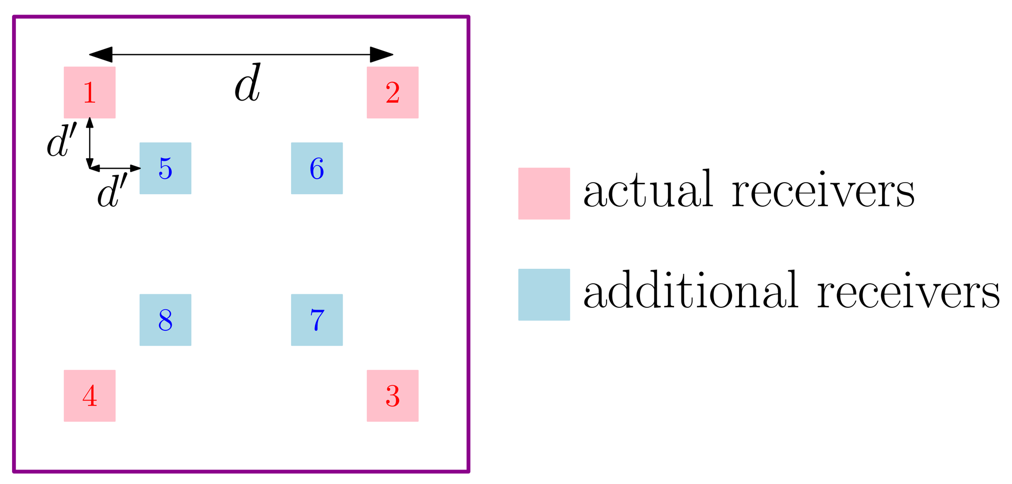


Figure 1: 2X spatial oversampling within the same form factor.

✓ Spatial oversampling is natural as distance b/w actual receivers $d = 34$ cm $>> \lambda$

Basic ZF conditions

1. $N_r \geq N_t$
2. The window length
$$W \geq W_0 = \left\lceil \frac{L-1}{\left(\frac{N_r}{N_t}\right) - 1} \right\rceil$$
3. $\mathbf{H}$ has full column rank

Table 1: Trade-off between N_r and W_0 for $L = 6$ and $N_t = 4$

N_r	5	6	7	8
W_0	20	10	7	5

✓ Time domain complexity reduces as spatial oversampling increases

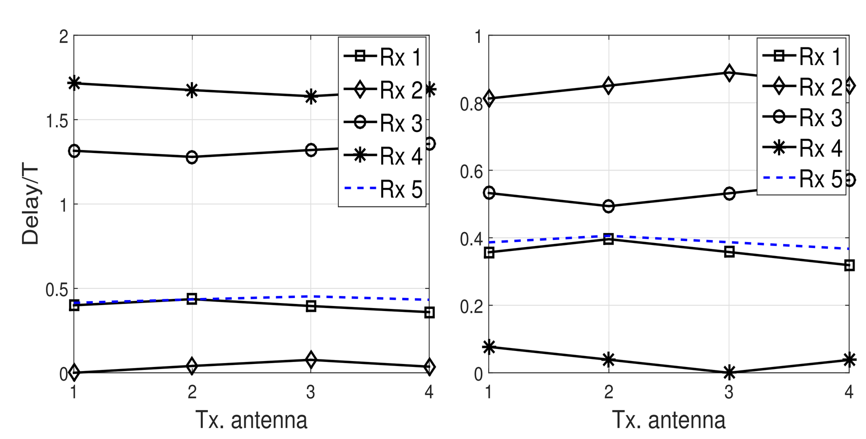


Figure 2: The variation of delays at the different receive antennas

- $\mathbf{H}$ is not a well-conditioned channel!
- Offset sampling (T/2 a robust choice) for additional antennas helps in obtaining a well-conditioned channel

Numerical results

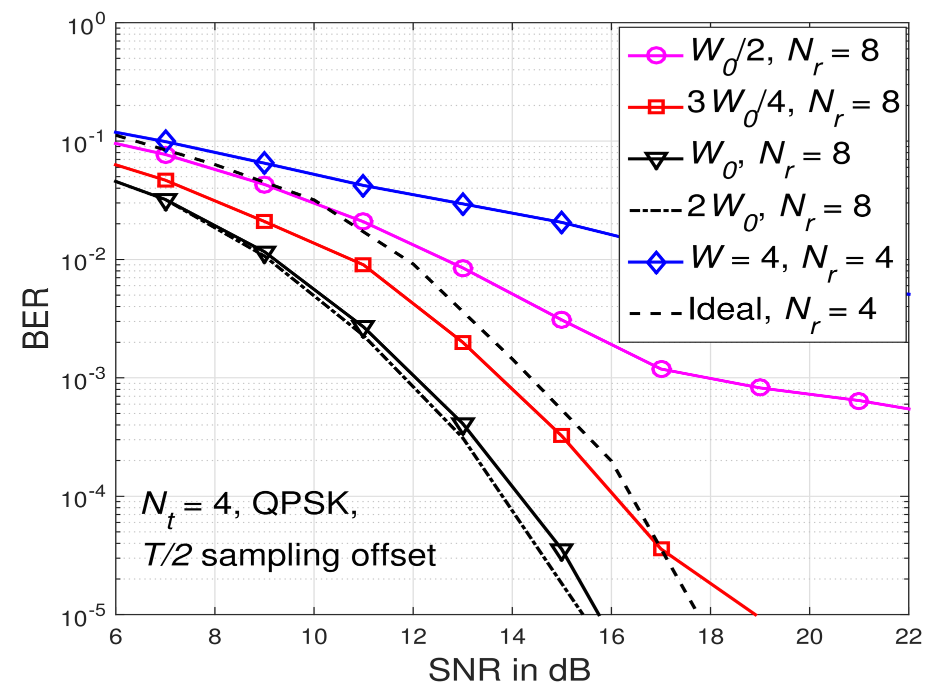


Figure 3: BER of the proposed oversampled LoS MIMO system for different window lengths with $N_t = 4$ and QPSK

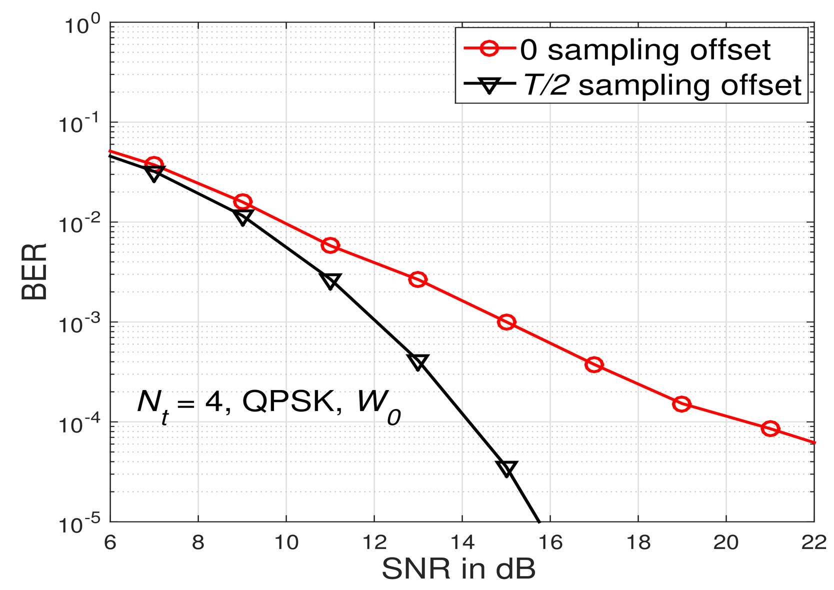


Figure 4: BER of the proposed oversampled LoS MIMO system for different sampling offsets at extra receive antennas

→ Performance improves with window length until W_0 and saturates thereafter
→ Window length of W_0 and $T/2$ sampling offset are necessary to avoid error floors
→ Misaligned system with $N_r = 8$ performs better than an ideally aligned system with $N_r = 4$ due to better noise averaging

Conclusion

1. Geometric misalignments in LoS MIMO cause frequency selectivity
2. Spatial oversampling, along with *designed* delay diversity, is an effective approach to combat the frequency selectivity
3. Can trade spatial oversampling against time complexity
4. Particularly attractive architecture: double the number of receivers within the same form factor

References

[1] E. Torkildson, U. Madhow, and M. Rodwell, "Indoor millimeter wave MIMO: Feasibility and performance," *IEEE Trans. Wireless Commun.*, vol. 10, no. 12, pp. 4150-4160, Dec. 2011.

[2] B. Mamandipoor, M. Sawaby, A. Arbabian, and U. Madhow, "Hardware-constrained signal processing for mmWave LoS MIMO," *in IEEE 49th Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, Nov. 2015.

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