A Study of LOS MIMO for Short-Range Sub-THz Wireless Links

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Agenda

- Introduction and Motivation
- Sub-THz Comm.: Link budget and performance at 240 GHz
- Principles of LOS MIMO
- System Study: 3x3 and 4x4 MIMO at 240 GHz
- Conclusion and Future work

Introduction and Motivation

- The need for data rates is increasing
- New services and applications (data centers, data showers, WLAN/WPAN, backhaul, …) are demanding more and more wireless data rates
- New frequency bands, mmWave, (Sub-)THz, with large chunks of free bandwidth allow for high data rates but there are challenges (path loss, signal processing, radio-electronics, etc)
- Several works recently reported short-range SISO links above 200 GHz demonstrating up to 100 Gb/s
- To breach the 100 Gb/s barrier and increase further the data rate, some form of MIMO multiplexing is required

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Line-of-sight MIMO multiplexing

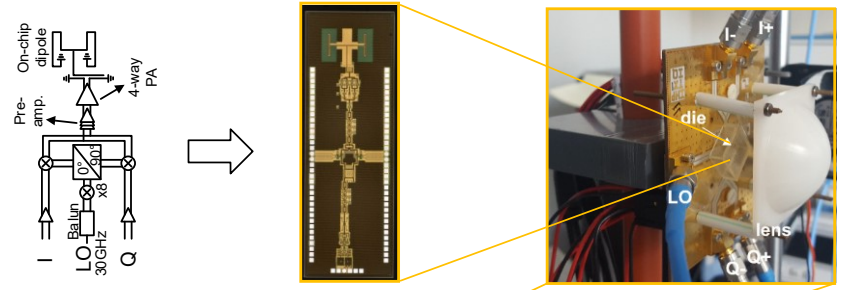
Sub-THz Comm.: Link budget and Performance at 240 GHz

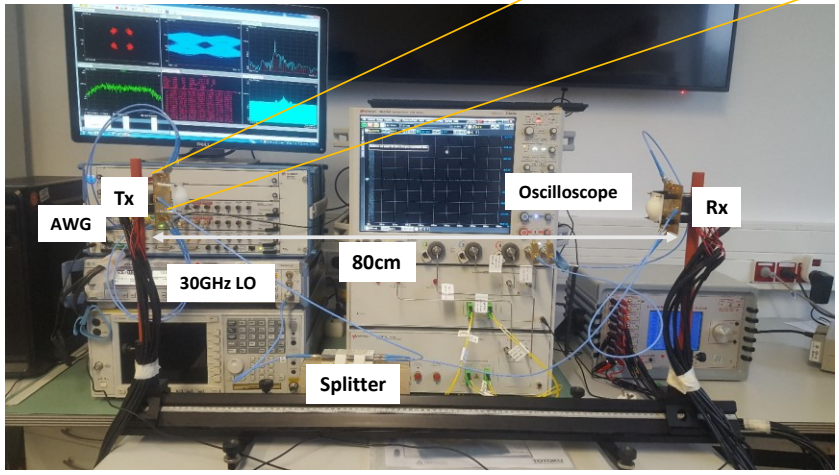
- Example of a link budget at TX-RX distance of 1-m in the J-band (240 GHz)
- Input parameters from measurement of real chips (Tx power, antenna gain, NF, etc)

Eissa et al. *TMTT* 2020
Maletic et al. *MTTW'*20

Carrier Frequency	240 GHz			
Distance	1 m			
Bandwidth	5 GHz	15 GHz	25 GHz	35 GHz
Transmit Power	5 dBm			
TX/RX Antenna Gain	7 dBi			
TX/RX Lens Gain	14 dB			
Path Loss	-80 dB			
Implementation Loss	-8 dB			
Received Level	-41 dBm			
Thermal Noise	-77 dBm	-72.2 dBm	-70 dBm	-68.5 dBm
Noise Figure	15 dB			
RX SNR	**21 dB**	**16.2 dB**	**14 dB**	**12.5 dB**
Modulation	64-QAM	16-QAM	16-QAM	8-PSK
Required SNR @ BER = 10^{-2}	*19.8 dB*	*13.8 dB*	*13.8 dB*	*12.1 dB*
Expected Data Rate	*30 Gb/s*	*60 Gb/s*	*100 Gb/s*	*105 Gb/s*

Sub-THz Comm.: Link budget and Performance at 240 GHz





Eissa et al. *TMTT* 2020
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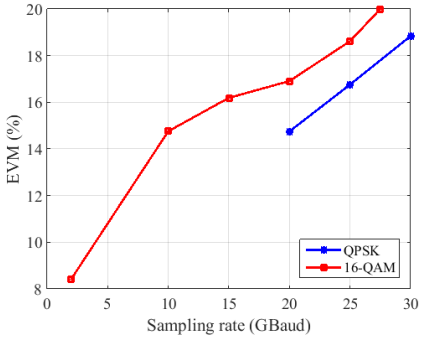
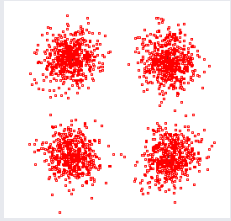
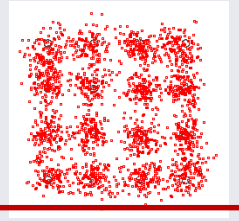
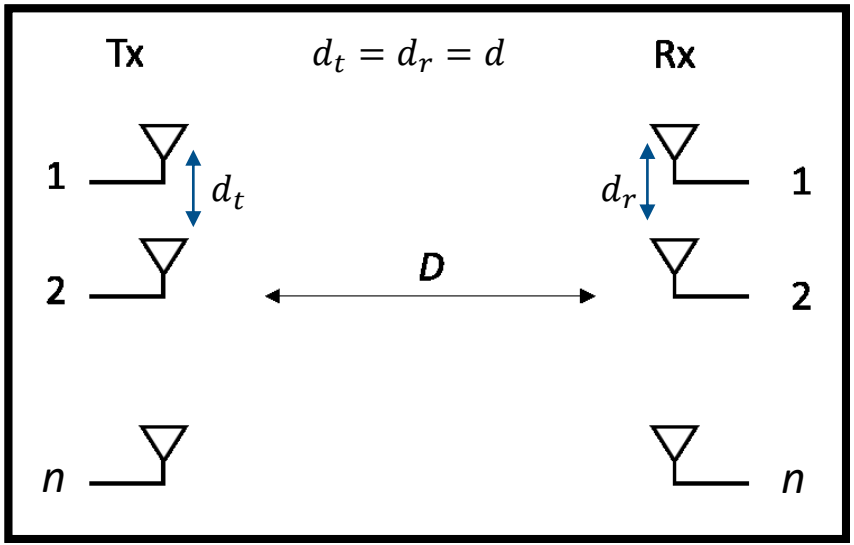


Modulation	QPSK	16-QAM
Data rate	40 Gbd → 80 Gb/s	27.5 Gbd → 110 Gb/s
Const. plot		
E2E EVM	28% (-11 dB)	20% (-14 dB)

At the FEC limit. How to further increase the data rate?

Principles of LOS MIMO

An *nxn* symmetrical MIMO link



$$\mathbf{H} = \begin{bmatrix} h_{11} & \cdots & h_{1n} \\ \vdots & \ddots & \vdots \\ h_{n1} & \cdots & h_{nn} \end{bmatrix}, \quad h_{u,v} = \exp(-j\frac{2\pi}{\lambda} r_{u,v}),$$

Condition for max multiplexing gain

$$d^2 = d_{opt}^2 = p \cdot \lambda D/n$$

$\mathrm{tr}(\mathbf{H}(D)\mathbf{H}^H(D)) = n^2$

Shannon capacity (Gaussian signaling)

$$C = \log_2 \det\left(\mathbf{I}_n + \frac{SNR}{n}\mathbf{H}\mathbf{H}^H\right)$$

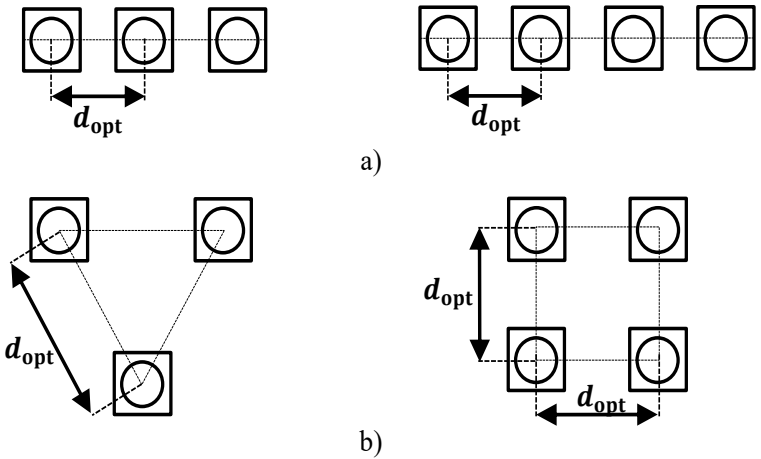
Capacity of practical signaling

$$C = n\log_2 M - \frac{1}{M}\sum_{l=1}^{M^n} \mathrm{E}_{\mathbf{w}}\left\{\log_2 \sum_{k=1}^{M^n} e^{-z_{l,k}}\right\}$$

$$z_{l,k} = \frac{\|\mathbf{H}(\mathbf{x}_l - \mathbf{x}_k) + \mathbf{w}\|_2^2 - \|\mathbf{w}\|_2^2}{\sigma_n^2}$$

System analysis for 3x3 and 4x4 LOS MIMO

Exemplifying MIMO configurations:
3x3 and 4x4 linear or planar



D =1 m, λ = 1.25 mm (f = 240 GHz)

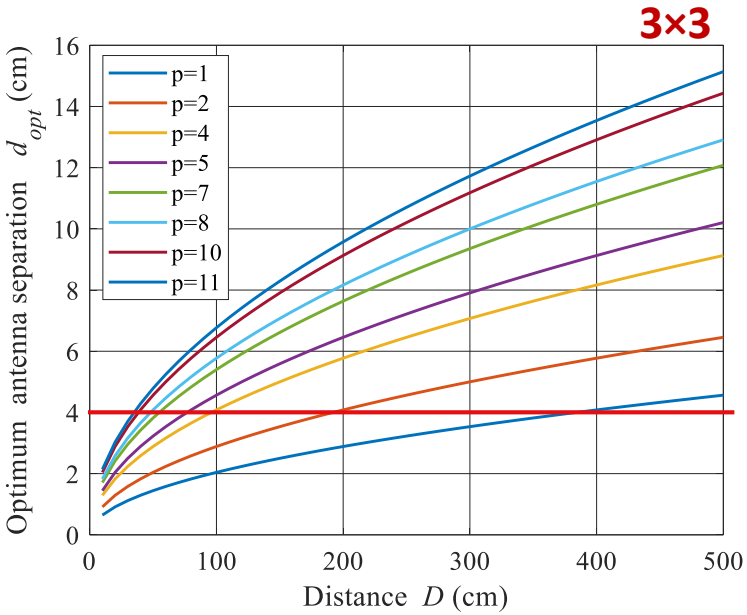
$$d_{opt}^2 = p \cdot \lambda D/n$$

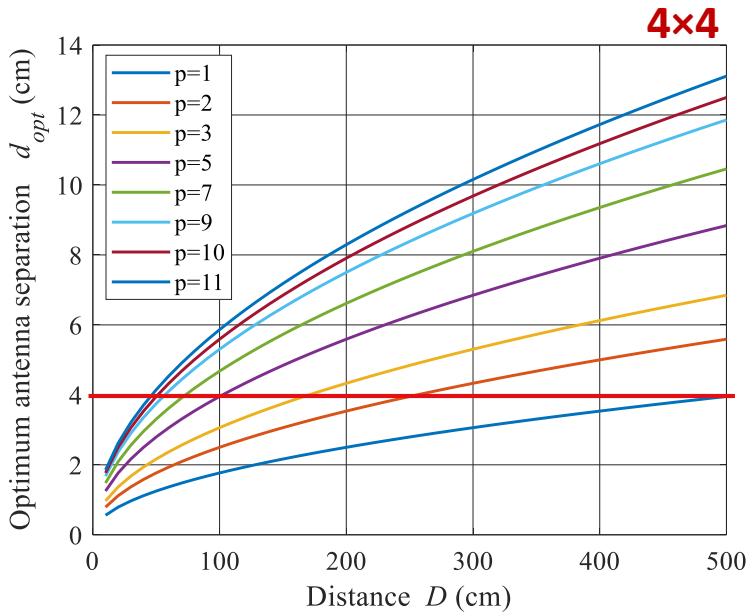
3×3		4×4	
p	d_{opt} (cm)	p	d_{opt} (cm)
1	2.0412	1	1.7678
2	2.8868	2	2.5000
4	4.0825	3	3.0619
5	4.5644	5	3.9528
7	5.4006	6	4.3301
8	5.7735	7	4.6771
10	6.4550	9	5.3033
11	6.7700	10	5.5902
13	7.3598	11	5.8630
14	7.6376	13	6.3738
16	8.1650	14	6.6144

For particular D, several choices for d_{opt} exist!

Sub-THz LOS MIMO: Optimum antenna separation

- d_{opt} as a function of range D





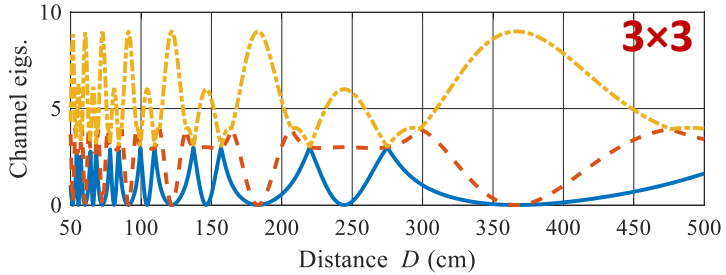
- For particular d_{opt} channel H has a full rank at several distances D
- E.g. d_{opt} = 4 cm D = {34.9091, 38.4, 48, 54.8571, 76.8, 96, 192, 384} cm for a 3×3 MIMO link

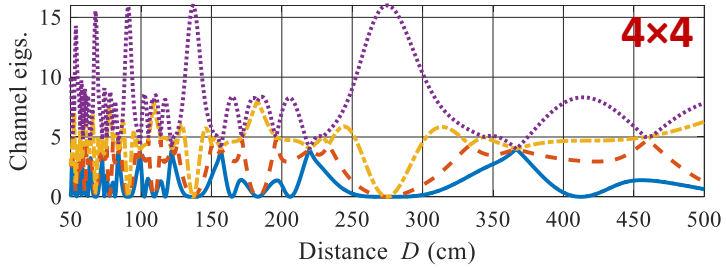
Sub-THz LOS MIMO: channel eigenvalues and Shannon capacity

- p = 11 and D = 1 m
- d_{opt} = 6.77 cm for 3×3 and 5.863 cm for 4×4

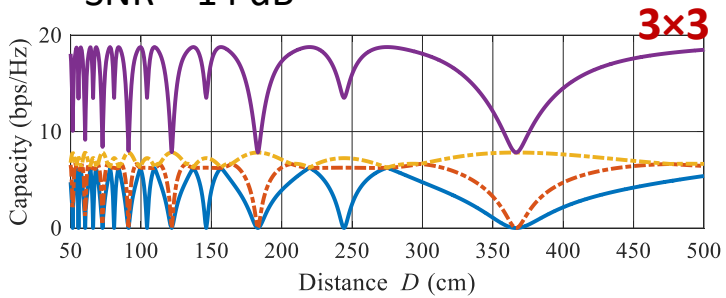
$$C = \log_2 \det\left(\mathbf{I}_n + \frac{SNR}{n}\mathbf{H}\mathbf{H}^H\right)$$

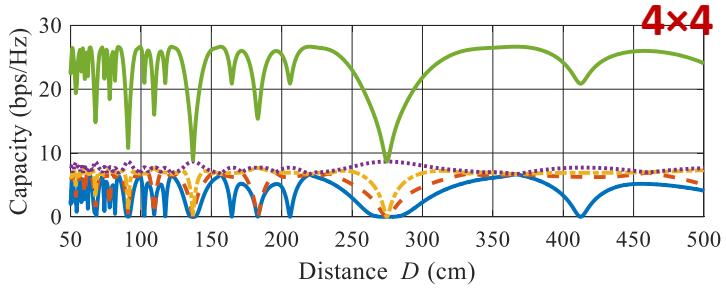
eig($\mathbf{H}(D)\mathbf{H}^H(D)$)





SNR = 14 dB





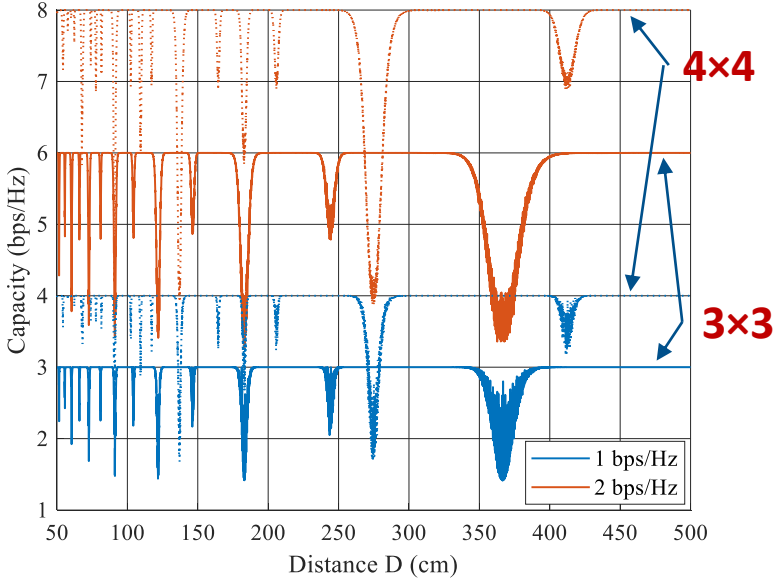
Sub-THz LOS MIMO: capacity of practical signaling

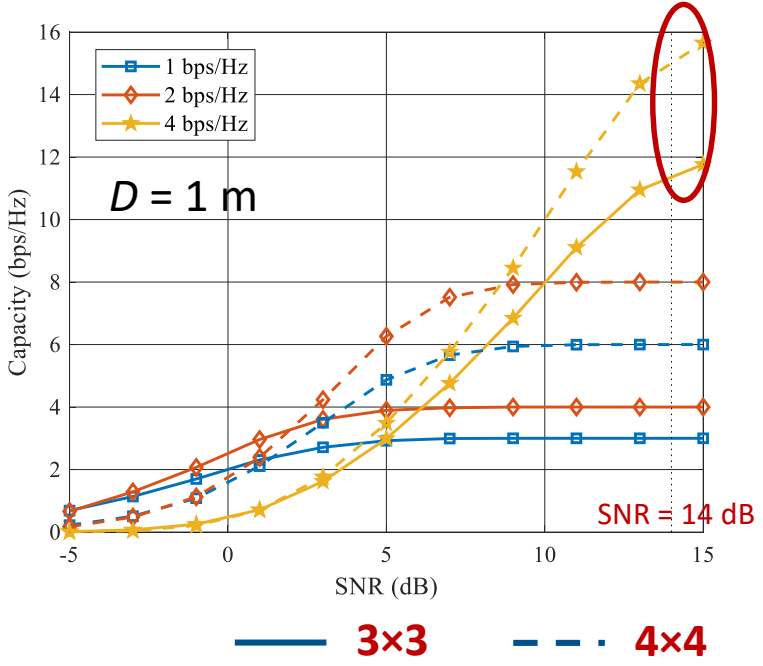
Practical signaling, e.g., M-PSK, M-QAM, M-PAM

Fixed d_{opt} = 6.77 cm for 3×3 and 5.863 cm for 4×4

SNR is not high enough to achieve max capacity for 4 b/s/Hz

SNR = 14 dB





Conclusion and Future Work

- (Sub-)THz communication supports high data rates but there are challenges
- Several works have already demonstrated 100 Gbps at short-range using highly integrated radio front-ends
- A simple study for 3x3 and 4x4 LOS MIMO links at 240 GHz examined the effects of optimum antenna separation and communication distance on channel and capacity
- LOS MIMO has a potential to further increase the throughput towards 1 Tb/s
- Experimental demonstration of LOS MIMO at (Sub-)THz frequencies (e.g. 240 GHz) using proprietary radios as a future work

Thank you for your attention!

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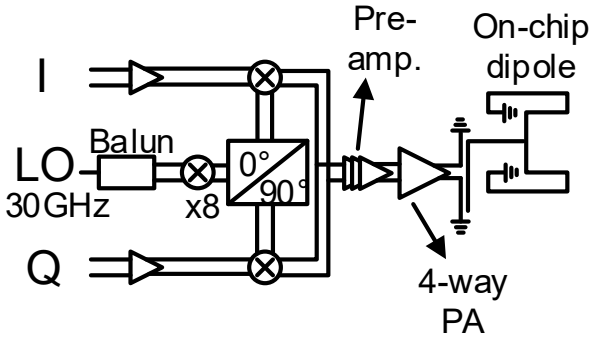
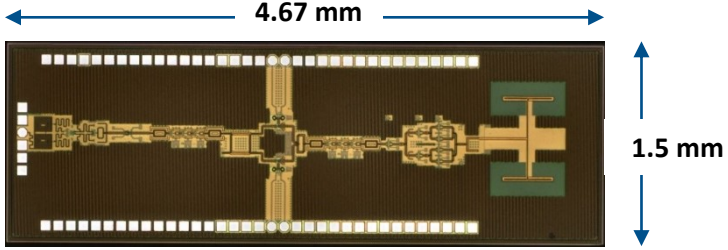
Backup slides

240-GHz Transmitter

- Transmitter chip



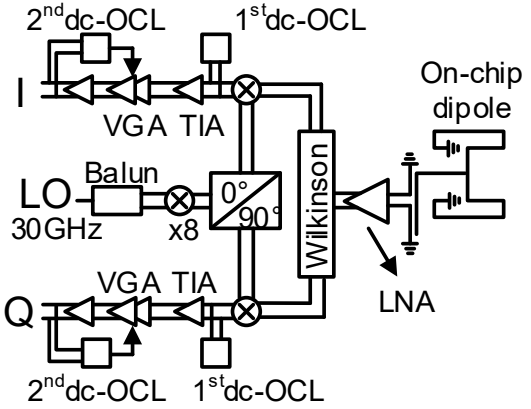


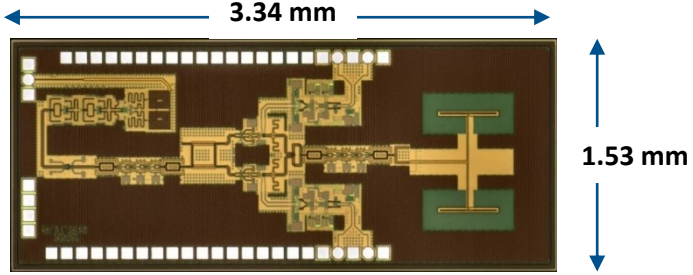
- 130nm SiGe f_t/f_{max} = 300/500 GHz (IHP)
- Zero-IF architecture for wideband performance
- Differential inputs
- RF bandwidth 35 GHz
- BB bandwidth 17.5 GHz
- Max gain 35 dB
- P_{sat} 12 dBm
- DC power 1.24 W
- Area 7 mm sq.
- On-chip double folded dipole with LBE to enhance directivity
- Mounted on a PCB with plastic lens

[M. H. Eissa et al, "100 Gbps 0.8-M Wireless Link based on Fully Integrated 240GHz IQ Transmitter and Receiver", in proc. MTT-S IMS, Jun 2020]

240-GHz Receiver

- Receiver chip





- 130nm SiGe f_t/f_{max} = 300/500 GHz (IHP)
- Zero-IF architecture for wideband performance
- Differential outputs
- RF bandwidth 55 GHz
- BB bandwidth 27.5 GHz
- Max gain 41 dB (tunable 25 dB)
- Noise figure 15 dB
- DC power 0.85 W
- Area 5.1 mm sq.
- On-chip double folded dipole with LBE to enhance directivity
- Mounted on a PCB with plastic lens

[M. H. Eissa et al, "100 Gbps 0.8-M Wireless Link based on Fully Integrated 240GHz IQ Transmitter and Receiver", in proc. MTT-S IMS, Jun 2020]

