Technical University Munich

In cooperation with

Channel Capacity Comparison of mmWave Receiver Concepts

Kilian Roth[1 2], Javier Garcia[2], Jawad Munir[2], Michael Faerber[1], Josef A. Nossek[2]

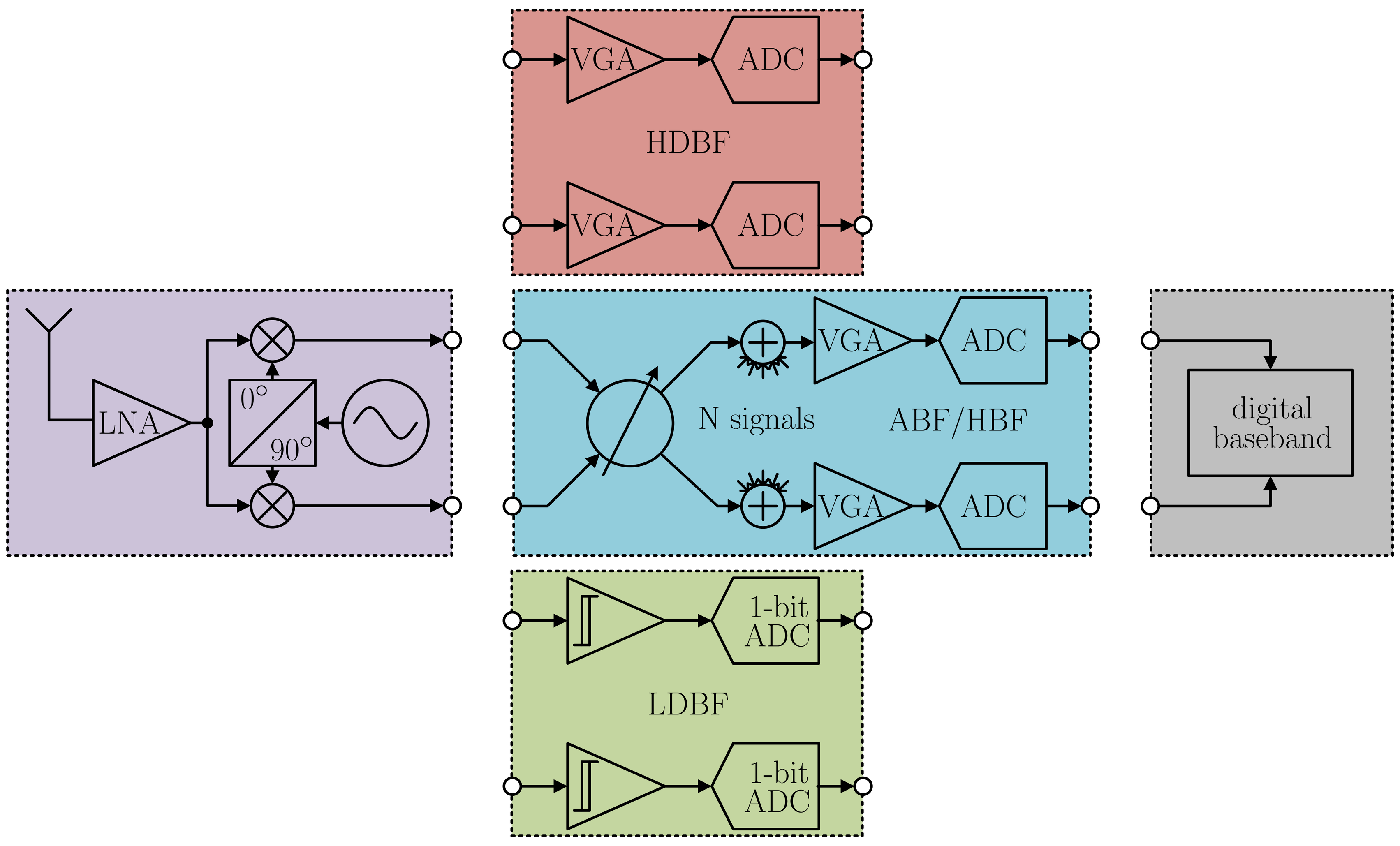
[1] Next Generation and Standards, Intel Deutschland GmbH, Neubiberg, Germany Email: {kilian.roth, michael.faerber}@intel.com

[2] Institute for Circuit Theory and Signal Processing, Technical University Munich, Munich, Germany Email: {kilian.roth, javier.garcia, jawad.munir, josef.a.nossek}@tum.de

Motivation

- mmWave systems operate at low SNR (per antenna)
- System limited by the power consumption (especially at the UE)
- Different receiver architectures possible
- Actually power consumption of the different architectures unknown
- How many antennas with 1-bit quantization can be used per antenna with full resolution ADC at equal power consumption ?
- Performance comparison of different solution at equal RF frontend power consumption

Systems Block Diagram



HDBF	High resolution A/D conversion Digital Beam Forming
ABF/HBF	Analog Beam Forming / Hybrid Beam Forming
LDBF	Low resolution A/D conversion Digital Beam Forming

Component Power Consumption

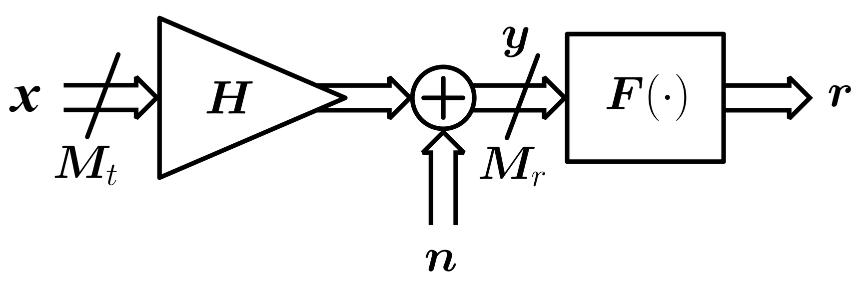
System parameters:

- Carrier-frequency 60 GHz
- Systembandwidth 2 GHz
- LO shared by all antennas
- Baseband power consumption assumed similar
- Reported designs in scientific publications not fully reliable

component	power consumption
LO	22.5mW
LNA	5.4mW
Mixer	0.3mW
90° hybrid and LO buffer	3.0mW
LA	0.8mW
1-bit ADC	≈ 0mW
phase shifter	2.0mW
VGA	2.0mW
ADC (8 ENOB)	10.0mW

system name	number of antennas M_r	power consumption	calculation formula
HDBF	3	121.5mW	$(33M_r + 22.5)$mW
ABF	7	123.5mW	$(11M_r + 24 + 22.5)$mW
LDBF	10	128.5mW	$(10.6M_r + 22.5)$mW

Signal Model



Symbol description:

$\boldsymbol{x}$	transmit signal
$\boldsymbol{H}$	channel
$\boldsymbol{n}$	noise
$\boldsymbol{y}$	receive signal
$\boldsymbol{r}$	receive
M_t	Number of transmitter antennas
M_r	Number of receiver antennas
M_{rRFE}	Number of antennas for one RFE-chain

Operator $F(\cdot)$ different for each system:

HDBF	$F_\infty(\boldsymbol{y}) = \boldsymbol{y}$
ABF	$F_{a/h}(\boldsymbol{y}) = \boldsymbol{W}\boldsymbol{y}$ with $w_{i,j} = e^{\phi_{i,j}}$ $\boldsymbol{w}_i = \left[1, e^{j\phi_i}, e^{j2\phi_i}, \cdots, e^{j(M_{rRFE}-1)\phi_i}\right]$
LDBF	$F_1(\boldsymbol{y}) = Q_1(\boldsymbol{y})$ $Q_1(\boldsymbol{y}) = \mathrm{sign}(\Re(\boldsymbol{y})) + \mathrm{j}\cdot\mathrm{sign}(\Im(\boldsymbol{y}))$

Capacity Expressions

Assumptions:

- Perfect CSI at the transmitter
- High resolution D/A conversion at each transmit antenna
- Perfect CSI at the receiver for HDBF and LDBF
- Optimal spatial direction know for ABF

HDBF channel capacity (waterfilling solution):

$$R_{HDBF}(\boldsymbol{H}) = \sum_{i=1}^{rank(\boldsymbol{H})} \log_2\left(1 + P_i \frac{D_i^2}{\sigma_n^2}\right)$$
$$\text{with } P_i = \max\left(\left(\mu - \frac{\sigma_n^2}{D_i^2}\right), 0\right) \text{ and } \sum_{i=1}^{M_t} P_i = P_t \quad (1)$$

ABF channel capacity:

$$R_{ABF}(\boldsymbol{H}) = \log_2\left(1 + \frac{\left|\left|\boldsymbol{w}^H(\hat{\phi})\boldsymbol{H}\right|\right|_2^2}{M_r\sigma_n^2}\right)$$
$$\text{with } \hat{\phi} = \underset{\phi}{\mathrm{argmax}} \left|\left|\boldsymbol{w}^H(\phi)\boldsymbol{H}\right|\right|_2^2 \text{ and } \boldsymbol{w}^H(\hat{\phi}) = \left[1, e^{j\hat{\phi}}, e^{j2\hat{\phi}}, \cdots, e^{j(M_r-1)\hat{\phi}}\right] \quad (2)$$

LDBF channel capacity lower bound:

- Bound is tight in the low SNR regime
- Bound is loose in the high SNR regime

$$R_{LDBF}(\boldsymbol{H}) = log_2\left|\boldsymbol{I}_{M_t} + \frac{\gamma}{M_t}\boldsymbol{H}^H \mathrm{diag}\left(\frac{1-\rho}{1+\rho\frac{\gamma}{M_t}||\boldsymbol{h}_i||_2^2}\right)\boldsymbol{H}\right| \quad (3)$$

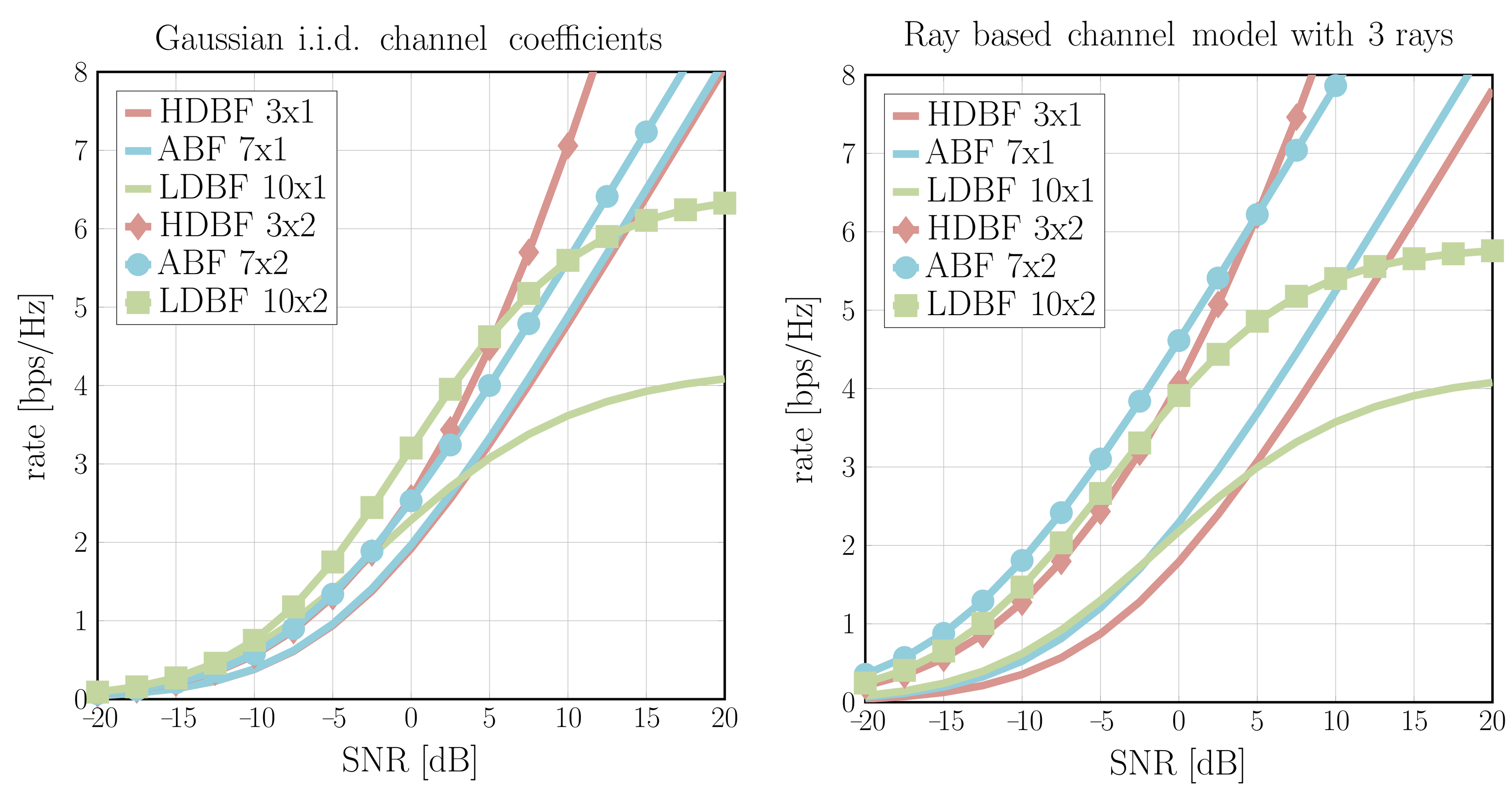
Symbol description:

D_i	ith eigenvalue of $\boldsymbol{H}$ in descending order	$\hat{\phi}$	optimal spatial angle
P_i	power allocated to the ith orthogonal channel with gain D_i	γ	transmit SNR $\frac{P_t}{\sigma_n^2}$
P_t	total transmit power	ρ	distortion factor dependen on A/D resolution 1-bit: 0.3634
σ_n^2	noise variance	$\boldsymbol{h}_i$	ith row of $\boldsymbol{H}$
ϕ	spatial angle		

Evaluation Results

Simulation description

- Gaussian i.i.d. channel coefficients represent a rich scattering environment
- Ray based channel model with a limited number of rays represent a LOS channel
- Rate is averaged over 1000 channel realizations
- Comparison of receivers with equal power consumption of the RF front-end



Conclusion

- Dependent on the channel substantial performance improvement possible
- Considering the beam alignment overhead additional improvement compared to ABF
- Specific HW design for low resolution is likely to further improve the power consumption of LDBF
- Link level simulation will show the implementation gap of the quantized MIMO systems