Channel capacity comparison of different system concepts for mmWave

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***Abstract*—For the next-generation mobile broadband standard, carrier frequencies in the range of 6 to 100 GHz are being considered. Communication at high carrier frequencies requires antenna arrays at both the base and mobile station. A 1-bit analog to digital converter can effectively reduce the complexity and power consumption of the analog front end. This is especially interesting in the context of large antenna arrays with a sizable signal bandwidth. The power consumption of the analog receiver frontend of analog beamforming, full resolution digital beamforming and 1-bit quantized digital beamforming are compared. This power model consists of reported components in the 60 GHz band. With this power model systems with equal power consumption and therefore different numbers of antennas are constructed. These systems are then compared in terms of channel capacity. In the low SNR region the performance of the system with 1-bit quantization clearly surpasses the performance with full resolution beamforming.**

***Index Terms*—1 Bit Quantization, Array Signal Processing, Millimeter Wave, Power Consumption, 60 GHz, Channel Capacity.**

I. Introduction

For the next generation mobile broadband standard (aka. 5G) higher carrier frequencies are being considered [1]. These frequencies are in the range from 6 to 100 GHz. Generally they are referred to as millimeter wave (mmW) even though the frequency range includes the lower centimeter wave range. The major advantage of utilizing this frequency range is the large available bandwidth. The base band (BB) and radio front end (RFE) capabilities must be drastically changed to fully leverage the different spectrum opportunities while maintaining most power-efficient ultra large bandwidth operation.

The use of high carrier frequencies above 6 GHz will go hand in hand with the implementation of massive antenna arrays [1], [2]. Radical new designs are needed for both TDD and FDD transmission schemes, accommodating a large number of antennas and RFEs at the base station and the user equipment. To attain a similar link budget the effective antenna aperture of a mmW system must be the comparable as for current systems operating at carrier frequencies below 6 GHz. Therefore an antenna array at the mobile and base station might be necessary. Since the antenna gain and therefore the directivity increases with the aperture an array is the only solution to attain a high effective aperture while maintaining an omnidirectional coverage.

Current LTE systems have limited amount of antennas at the base and mobile stations. Since the bandwidth is limited the power consumption of having a receiver RF chain with high resolution A/D converter at each antenna is still feasible. For future mmWave mobile broadband systems a much larger bandwdith [18] and a large number of antennas are being considered [1]. The survey [3] shows that A/D converters with a large sampling frequency and medium number of effective bits consume a considerable amount of power and can be considered as the bottleneck of the receiver [4].

The antenna array combined with the large bandwidth is a huge challenge for the hardware implementation, especially considering the power consumption. At the moment analog or hybrid beamforming are considered as a possible solution to reduce the power consumption. Analog or hybrid beamforming systems highly depends on the calibration of the analog components. Another major disadvantages is the dependency on the alignment of the Tx and Rx beams of the base and mobile stations. If a high antenna gain is needed the beamwidth is very small. This make the acquisition and constant alignment of the optimal beams in a changing environment very challenging [5], [6] and [7].

Digital beamforming has a prohibiting high power consumption for a mmWave system at the receiver of the mobile or base station. Therefore a solution that offers the full flexibility of MIMO with constrained power consumption would be to use a radio frontend behind each antenna with a low resolution ADC [8], [9] and [10]. In the extreme case that would mean utilizing a 1-bit ADC for the inphase and quadrature component of the signal. This receiver architecture has the advantage that an AGC is not needed, thus the VGA be replaced by a much simpler limiting amplifier. Because the 1-bit quantization represents a major non-linearity at the end of the receiver chain, the requirements on the linearity and dynamic range of the whole receiver chain is reduced. Therefore the power consumption of the hardware can be reduced without any further compromises in terms of performance and flexibility.

The contribution of this paper is to show the relative performance of the different schemes taking the power consumption into account. The power consumption is based on designs reported for the 60 GHz band but as long as a low cost CMOS implementation is considered the relative performance between the different receiver architectures should remain

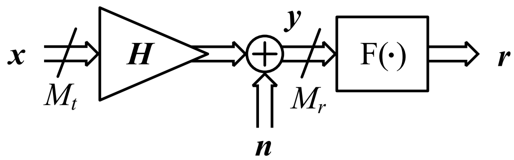

Fig. 1. Signal Model.

the same for a much wider frequency range. The power consumption of the digital signal processing is not taken into account. The power consumption of the digital signal processing is expected to decrease by a much larger amount relative to a implementation of today. The implementation complexity of the digital signal processing is also expected to be similar for the different systems.

Our paper is organized as follows: First the signal model is described. Then the power of the different receiver architectures are presented. The channel capacity for the different systems are then presented. At the end the channel capacity of different systems with equal power consumption are compared.

Throughout the paper we use boldface lower and upper case letters to represent column vectors and matrices. The term $a_{m,l}$ is the element on row m and column l of matrix $\boldsymbol{A}$ and a_m is the mth element of vector $\boldsymbol{a}$. The expressions $\boldsymbol{A}^*$, $\boldsymbol{A}^T$, $\boldsymbol{A}^H$ and $\boldsymbol{A}^{-1}$ represent the complex conjugate, the transpose, the hermitian and the inverse of the operand. The symbol $\otimes$ is the Kronecker product.

II. Signal Model

The signal model is shown in Figure 1. The terms $\boldsymbol{x}$, $\boldsymbol{H}$, $\boldsymbol{n}$ and $\boldsymbol{y}$ represent the transmit signal, channel, noise and receiver signal at a system with M_t transmit and M_r receive antennas. The operation $F(\cdot)$ is different for the analog/hybrid beamforming and low/high resolution digital beamforming. In the case of analog/hybrid beamforming it is equal to multiplying with a matrix $\boldsymbol{W}$:

$$\boldsymbol{r}_{a/h} = F_{a/h}(\boldsymbol{y}) = \boldsymbol{W}\boldsymbol{y}. \tag{1}$$

The matrix $\boldsymbol{W}$ is representing the phase shifts at each antenna element. Therefore each entry is only a phase rotation with magnitude one. The matrix $\boldsymbol{W}$ has M_{RFC} row and M_r columns. In the case of analog beamforming M_{RFC} is equal to one. If it is greater than one we speak of hybrid beamforming.

For digital beamforming with high resolution the distortion generated by the A/D conversion is negligible and thus $F(\cdot)$ and r_∞ is equal to $\boldsymbol{y}$:

$$\boldsymbol{r}_\infty = F_\infty(\boldsymbol{y}) = \boldsymbol{y}. \tag{2}$$

In the case of 1-bit quantization $F(\cdot)$ is equal to the quantization operation with 1-bit $Q_1(\cdot)$:

$$\boldsymbol{r}_1 = F_1(\boldsymbol{y}) = Q_1(\boldsymbol{y}). \tag{3}$$

The 1-bit quantization operation $Q_1(\cdot)$ is defined as follows:

$$Q_1(\boldsymbol{y}) := \mathrm{sign}(\Re(\boldsymbol{y})) + \mathrm{j}\cdot\mathrm{sign}(\Im(\boldsymbol{y})). \tag{4}$$

The sign$(\cdot)$ function is operating separately on each element of the vector or matrix it is defined as:

$$\mathrm{sign}(a) := \begin{cases} 1, & a > 0 \\ -1, & a \leq 0 \end{cases}. \tag{5}$$

III. Assessment of the Power Consumption

In a future 5G millimeter Wave mobile broadband system it will be necessary to utilize large antenna arrays. In general the power consumption of the analog front-end of a large antenna array is high. It is therefore important to compare the power consumption of different beamforming architectures. In this section we compare the power consumption of analog/hybrid beamforming to digital beamforming and the proposed digital beamforming architecture with 1-bit quantization.

Since the spectrum in the 60 GHz band can be accessed without a license it got significant attention. Especially the WiGig (802.11ad) standard operating in this band significantly extended the transmitter and receiver RF hardware R&D activities. Therefore there are many chips being reported in industry and academia. Thus it is save to assume that the design reached a certain maturity and performance figures derived from them represent the performance that is possible for a low cost CMOS implementation today.

According to the discussion in [11] baseband or IF phase shifting in contrast to RF phase shifting is assumed. This has the advantage of increased accuracy, decreased insertion loss and reduced gain mismatch. In [11] the authors showed that the power consumption is equivalent to a system utilizing RF phase shifters.

All three systems utilize the same direct conversion receiver (Figure 2). The local oscillator (LO) is shared by all antennas in the module. After the signals are converted into inphase and quadrature component the analog baseband (BBI and BBQ) the additional circuit is different for each of the systems. The analog baseband circuit of the full resolution digital beamforming system only consists of a variable gain amplifier (VGA) and a full resolution ADC for the I and Q path at each antenna (Figure 3). In contrast the 1-bit quantized digital beamforming does not need a variable gain, because we do not need to adjust the gain to use the full dynamic range of the ADC. Therefore the circuit consists only a limiting amplifier (LA) and the 1-bit ADC (Figure 5). Figure 4 shows the analog baseband block diagram for one radio frontend chain. Here the signals of N antennas are phase shifted and the combined by an analog combiner. N is defined as the number of receive antennas M_r divided by the number for RF chains M_{RFC}. Afterwards the I and Q path are amplified with a VGA and then A/D converted by a full resolution ADC. Depending on the total number of receive antennas M_r and M_{RFC} RF-chains this system is denoted as analog or hybrid beamforming. The number of antennas is always lager or equal to than the number of RF-chains $M_r > M_{RFC}$. For $M_{RFC} = 1$ the system is using pure analog beamforming. Otherwise a hybrid analog/digital beamforming architecture is used.

The power consumption of each component including a reference are summarized in Table I. A LO with a power

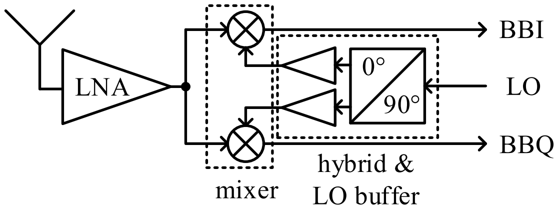

Fig. 2. Common circuit blocks of all systems.

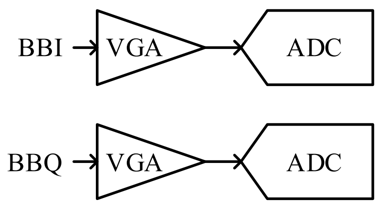

Fig. 3. Baseband digital beamforming system.

consumption as low as 22.5mW is reported in [12]. The power consumption of a LNA, a mixer including a quadrature-hybrid coupler and a VGA are reported in [13] with 5.4, 0.5 and 2mW. The 90° hybrid and the clock buffer reported in [14] have a power consumption of 3 mW. The power consumption of the mixer reported in [15] is even as low as 0.3mW. The survey in [3] always gives a good overview of state of the art ADCs in terms of effective number of bits (ENOB), sampling rate and power consumption. From the survey and examples like [16] and [17] we can extrapolate that for an ADC with about 8 ENOB and 1.5 to 2GS/s the power consumption is at best around 10mW. Here we assume a maximal signal bandwidth of 1 GHz as in [18]. A limiting amplifier (LA) is reported in [19] consumes 0.8mW. In the 1-bit quantized system the LA (aka. Schmitt trigger) is already producing a digital signal, therefore the 1-bit ADC can be replaced by a flip flop (FF). The power consumption of a FF is negligible compared to the rest of the circuit. Figure 6 shows the power consumption of different systems. Here an analog, a digital, a hybrid and a 1-bit beamforming system are compared in terms of power consumption according to the buildings blocks in Table I. For the hybrid beamforming 2 RF chains are used. Since addition power consumption per additional antenna is roughly the same the slope of the power consumption for

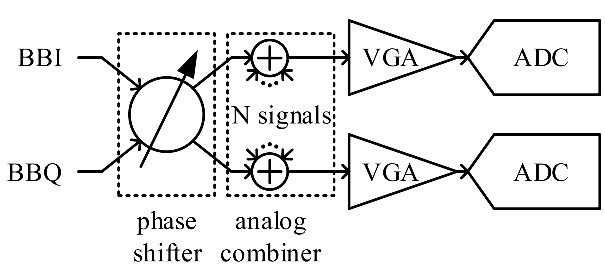

Fig. 4. Baseband analog/hybrid beamforming system.

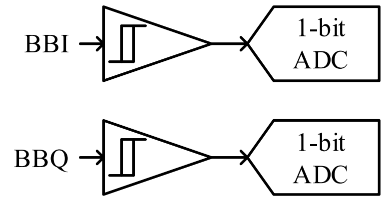

Fig. 5. Baseband 1-bit digital beamforming system.

TABLE I
COMPONENTS WITH POWER CONSUMPTION.

component	power consumption	reference
LO	22.5mW	[12]
LNA	5.4mW	[13]
Mixer	0.3mW	[15]
90° hybrid and LO buffer	3mW	[14]
LA	0.8mW	[19]
1-bit ADC	0mW	
phase shifter	2mW	[20] [11]
VGA	2mW	[13]
ADC	10mW	[3], [16] and [17]

digital, hybrid and 1-bit beamforming is similar. Only the full resolution digital beamforming has a much higher power consumption associated with each additional antenna element. Overall this lead to the fact that the power consumption of full resolution digital beamforming is prohibiting high for large antenna arrays. In Figure 7 shows the maximum number of antennas a system can have give the power consumption. Between the 1-bit or the analog beamforming there is roughly a factor of 3 in the number of antennas. This can be easily

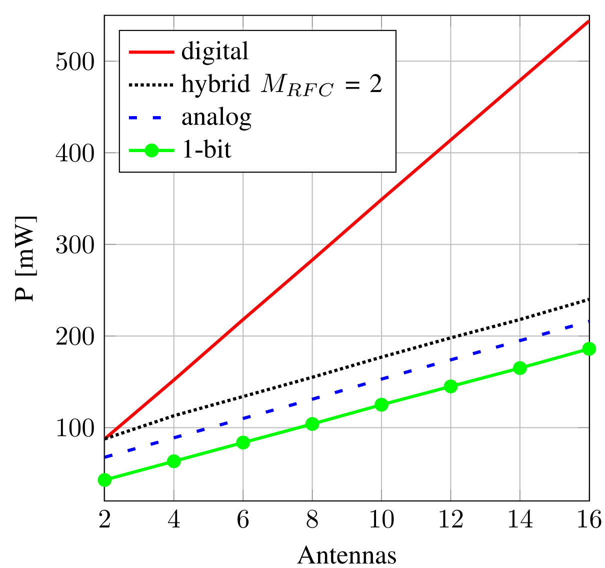

Fig. 6. Power consumption of analog, hybrid, digital and 1-bit beamforming.

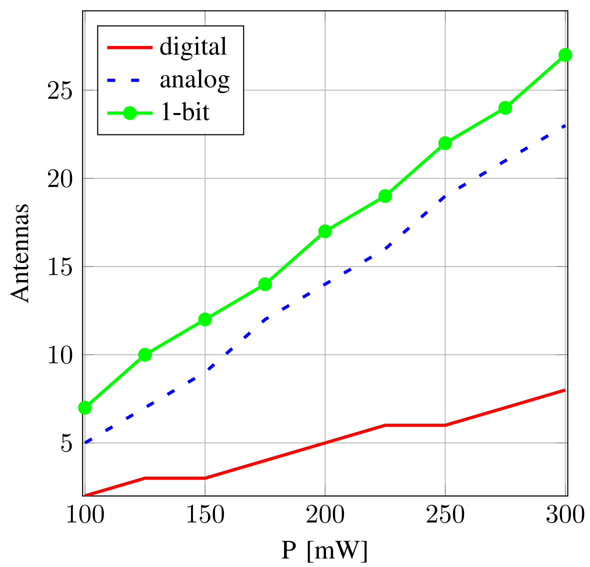

Fig. 7. Maximum number of antennas for given power consumption.

TABLE II
POWER CONSUMPTION PER ANTENNA ELEMENT.

system	power consumption per antenna
digital beamforming	32.6mW
analog beamforming	10.6mW
1-bit beamforming	10.2mW

derived from the power consumption per additional antenna at show in Table II. For the system with 1-bit quantization it is very likely that a receiver directly designed for this receiver topology would improve the power consumptions even further. Through the 1-bit quantization at the end of the receiver the linearity required of the circuits before is greatly reduced. This would enable specialized designs to improve the performance in terms of power consumption. In this analysis we showed that the power consumption per antenna for the architecture with high resolution is around 3 times higher than for the system with a 1-bit ADC with state of the art components. This does not include any hardware that is specialized for the 1-bit resolution case, therefore in a practical system the power consumption could even be lower. For the rest of the evaluation we use this power difference to compare two systems with equal power consumption.

IV. Channel Capacity with different Receiver Architectures

V. Simulation Results

VI. Conclusion

References

[1] F. Boccardi, R. Heath, A. Lozano, T. Marzetta, and P. Popovski, "Five disruptive technology directions for 5g," *Communications Magazine, IEEE*, vol. 52, no. 2, pp. 74–80, February 2014.

[2] J. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. Soong, and J. Zhang, "What will 5g be?" *Selected Areas in Communications, IEEE Journal on*, vol. 32, no. 6, pp. 1065–1082, June 2014.

[3] B. Murmann, "Adc performance survey 1997-2015," *[Online]. Available: http://www.stanford.edu/ murmann/adcsurvey.html*, 2015.

[4] J. Singh, O. Dabeer, and U. Madhow, "On the limits of communication with low-precision analog-to-digital conversion at the receiver," *Communications, IEEE Transactions on*, vol. 57, no. 12, pp. 3629–3639, December 2009.

[5] C. Barati Nt., S. Hosseini, S. Rangan, P. Liu, T. Korakis, S. Panwar, and T. Rappaport, "Directional cell discovery in millimeter wave cellular networks," *Wireless Communications, IEEE Transactions on*, vol. PP, no. 99, pp. 1–1, 2015.

[6] T. Rappaport, R. Heath, R. Daniels, and J. Murdock, *Millimeter Wave Wireless Communications*, ser. Prentice Hall Communications Engineering and Emerging Technologies Series from Ted Rappaport. Pearson Education, 2014.

[7] J. Mo and R. Heath, "Capacity analysis of one-bit quantized mimo systems with transmitter channel state information," *Signal Processing, IEEE Transactions on*, vol. 63, no. 20, pp. 5498–5512, Oct 2015.

[8] J. A. Nossek and M. T. Ivrlac, "Capacity and coding for quantized mimo systems." in *IWCMC*, 2006.

[9] A. Alkhateeb, J. Mo, N. Gonzalez-Prelcic, and R. Heath, "Mimo precoding and combining solutions for millimeter-wave systems," *Communications Magazine, IEEE*, vol. 52, no. 12, pp. 122–131, December 2014.

[10] A. Mezghani and J. Nossek, "On ultra-wideband mimo systems with 1-bit quantized outputs: Performance analysis and input optimization," in *Information Theory, 2007. ISIT 2007. IEEE International Symposium on*, June 2007, pp. 1286–1289.

[11] J. Chen, "Advanced architectures for efficient mm-wave cmos wireless transmitters," Ph.D. dissertation, EECS Department, University of California, Berkeley, May 2014. [Online]. Available: http://www.eecs.berkeley.edu/Pubs/TechRpts/2014/EECS-2014-42.html

[12] K. Scheir, S. Bronckers, J. Borremans, P. Wambacq, and Y. Rolain, "A 52 ghz phased-array receiver front-end in 90 nm digital cmos," *Solid-State Circuits, IEEE Journal of*, vol. 43, no. 12, pp. 2651–2659, Dec 2008.

[13] Y. Shang, D. Cai, W. Fei, H. Yu, and J. Ren, "An 8mw ultra low power 60ghz direct-conversion receiver with 55db gain and 4.9db noise figure in 65nm cmos," in *Radio-Frequency Integration Technology (RFIT), 2012 IEEE International Symposium on*, Nov 2012, pp. 47–49.

[14] C. Marcu, "Lo generation and distribution for 60ghz phased array transceivers," Ph.D. dissertation, EECS Department, University of California, Berkeley, Dec 2011. [Online]. Available: http://www.eecs.berkeley.edu/Pubs/TechRpts/2011/EECS-2011-132.html

[15] Y. Jin, J. Long, and M. Spirito, "A 7db nf 60ghz-band millimeter-wave transconductance mixer," in *Radio Frequency Integrated Circuits Symposium (RFIC), 2011 IEEE*, June 2011, pp. 1–4.

[16] H.-K. Hong, H.-W. Kang, D.-S. Jo, D.-S. Lee, Y.-S. You, Y.-H. Lee, H.-J. Park, and S.-T. Ryu, "26.7 a 2.6b/cycle-architecture-based 10b 1 jgs/s 15.4mwx time-interleaved sar adc with a multistep hardware-retirement technique," in *Solid- State Circuits Conference - (ISSCC), 2015 IEEE International*, Feb 2015, pp. 1–3.

[17] B.-R.-S. Sung, D.-S. Jo, I.-H. Jang, D.-S. Lee, Y.-S. You, Y.-H. Lee, H.-J. Park, and S.-T. Ryu, "26.4 a 21fj/conv-step 9 enob 1.6gs/s 2x time-interleaved fati sar adc with background offset and timing-skew calibration in 45nm cmos," in *Solid- State Circuits Conference - (ISSCC), 2015 IEEE International*, Feb 2015, pp. 1–3.

[18] N. G. I. Team, "5G White Paper," NGNM, TS, 2015. [Online]. Available: https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

[19] A. Oncu, B. Badalawa, and M. Fujishima, "60ghz-pulse detector based on cmos nonlinear amplifier," in *Silicon Monolithic Integrated Circuits in RF Systems, 2009. SiRF '09. IEEE Topical Meeting on*, Jan 2009, pp. 1–4.

[20] L. Kong, "Energy-efficient 60ghz phased-array design for multi-gb/s communication systems," Ph.D. dissertation, EECS Department, University of California, Berkeley, Dec 2014. [Online]. Available: http://www.eecs.berkeley.edu/Pubs/TechRpts/2014/EECS-2014-191.html