Pathways towards Tb/s Wireless

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***Abstract*—As standardization on 100 Gb/s has been commenced within IEEE 802.11ay, research must focus on the next challenge: how to reach 1Tb/s over the wireless channel, either for very short range communications as needed in wireless backplanes of the future, or for wireless LAN for hot spot coverage. This implies addressing multiple bottlenecks in parallel. Firstly, the power consumption problem of transceiver design, clearly indicating that the analog-to-digital interface may become key. Secondly, the carrier frequency to be chosen, where only the mm-wave spectrum above 100 GHz shows enough available bandwidth. However, the link budget and channel characteristics as well as the performant integration of the RF components need careful analysis. Thirdly, the RF frontend architecture including the antenna array design requires a novel approach regarding the phase distribution network. This paper addresses these challenges and shows pathways on how solutions can be found.**

***Index Terms*—A/D-conversion, oversampling, runlgenth-coding, mmWave, Butler-matrix, RF-frontend, antennas**

I. Introduction

For wireless communication systems targeting data rates in the order of 100 Gb/s, standardization has already started within IEEE 802.11ay. Thus, research has to focus on even higher data rates in the 1 Tb/s regime already now. Wireless communication with such data rates will become important for applications like very short range board-to-board computer communications which will allow to substitute copper based wired backplanes as used in today's computers [1], [2]. Furthermore, also hotspot coverage in future wireless LAN systems will require such data rates. However, to achieve such high data data rates several problems need to be solved.

First of all, only the mm-wave spectrum above 100 GHz shows sufficient available bandwidth. Moreover, the available signal bandwidth scales with the carrier frequency, typically not more than 15% of the carrier frequency. Thus, carrier frequencies in the range of $100 - 300$GHz are considered for these systems. However, such frequencies pose new challenges on the RF frontend and the antenna design including the analysis of the channel characteristics and the link budget.

Moreover, the power consumption of the transceivers becomes critical. In this regard, especially the analog-to-digital converter consumes a significant share of the total energy of the link due to the very high sampling frequencies. To cope with this problem, we consider a very coarse grained analog-to-digital conversion with only one bit resolution, i.e., just resolving the sign of the signal. By oversampling the signal with respect to its bandwidth, we substitute amplitude resolution by time resolution. This improves the energy efficiency of the receiver as no sophisticated processing of the signal amplitude is necessary, i.e., the requirements on amplifier linearity are relaxed and an automatic gain control is not needed. Moreover, it allows to decrease the supply voltage of the ADC circuits as not much voltage headroom for amplitude processing is required such that its power consumption is decreased [3]. On the other hand, with the clock cycles of today's circuits becoming shorter, higher sampling rates are enabled. In addition, the effective sampling rate can be further increased by considering multi-core circuits which can be utilized in a time interleaved fashion. In summary, this motivates the use of a time domain signal processing instead of an amplitude domain signal processing to enable an energy-efficient analog-to-digital conversion.

In the rest of this work, we will show which data rates and spectral efficiencies are achievable with systems using a 1-bit quantization in combination with oversampling. Moreover, we will report on channel measurements to evaluate the channel characteristics and the link budget and we will discuss in more detail solutions for the RF frontends for very large bandwidth at carrier frequencies in the range of $100-300$GHz. These are two major steps to enable wireless communication with data rates towards Tbit/s.

II. Spectral Efficiency of Multigigabit/s-Communication with 1-Bit Quantization

When the amplitude information is discarded during the A/D-conversion of the received signal at the receiver, all transferred information is conveyed in the zero-crossings of the signal. Thus, the distances of those zero-crossings can be regarded as the information symbols. We assume a transmitted signal that is alternating between two levels $\sqrt{\hat{P}}$ and $-\sqrt{\hat{P}}$, with linear transitions, i.e., a triangular waveform with a peak power constraint. This concept is related to the so-called runlength-limited sequences [4], which are well known from the field of magnetic recording. There, a run is the number of consecutive alike symbols (± 1), constrained by a minimum and maximum runlength, respectively. Here, we constrain ourselves to a minimum runlength L_{min}, as we are mainly interested in shaping the spectrum of the transmit signal and

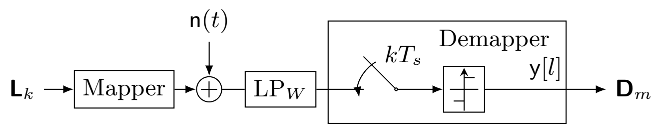

Fig. 1. System model

do not consider a maximum runlength. The input symbols L_k then are given by the number of time slots of length T_s, that are occupied by the corresponding symbols, where T_s is the time between two samples. The entropy maximizing distribution for a positive discrete random variable with given expectation is the geometric distribution ([5], Section 1.9.32), yielding for the entropy of the input process

$$H(\mathsf{L}_k) = (1+\tilde{\mu})\log(1+\tilde{\mu}) - \tilde{\mu}\log(\tilde{\mu}) \tag{1}$$

where $\tilde{\mu} = \mathbb{E}[\mathsf{L}_k] - L_{\text{min}}$. As the input symbols are assumed to be independent, this gives an entropy rate of

$$H'(\mathbf{L}) = \lim_{K\to\infty} \frac{H(L_1, L_2, ..., L_K)}{K\,\mathbb{E}[\mathsf{L}_k]T_s} \tag{2}$$

$$= \frac{(1+\tilde{\mu})\log(1+\tilde{\mu}) - \tilde{\mu}\log(\tilde{\mu})}{\mathbb{E}[\mathsf{L}_k]T_s}. \tag{3}$$

In the following, we will show that this scheme is well suited for the envisaged short range scenario and has a high spectral efficiency. The signal is transmitted over an additive white Gaussian noise channel depicted in Fig. 1 with power spectral density $N_0/2$. We assume sampling according to the receiver bandwidth with $T_s = \frac{1}{2W}$ and, hence, the noise samples are independent with variance $\sigma_{\mathsf{N}}^2 = N_0/2$. Note, that the samples of the received signal are not independent as L_k consecutive samples belong to one information symbol. If, e.g., some of the middle samples flip, the number of received symbols corresponding to one transmitted symbol can change. Hence, we are dealing with a insertion- and deletion-channel for which the capacity is unknown.

However, using the approach of an auxiliary process as, e.g., given in [6], we can lower-bound the information rate. Assuming the discrete auxiliary process $\mathbf{V}$ to be genie-aided information that enables the receiver to reverse all impairments introduced by the channel, we can write for the achievable rate, i.e., the mutual information rate

$$I'(\mathbf{L},\mathbf{D}) \geq I'(\mathbf{L};\mathbf{D},\mathbf{V}) - H'(\mathbf{V}) = H'(\mathbf{L}) - H'(\mathbf{V}) \tag{4}$$

where we make use of the genie-aided information, s.t. $I'(\mathbf{L};\mathbf{D},\mathbf{V}) = I'(\mathbf{L};\mathbf{L}) = H'(\mathbf{L})$. Most simply, $\mathbf{V}$ can be a binary sequence (± 1) to be multiplied with the received vector, indicating which samples are to be flipped (-1) and which not $(+1)$. As the noise samples are uncorrelated and all signal samples have the same magnitude, the samples of $\mathbf{V}$ are independent and the entropy rate of the auxiliary process follows as

$$H'(\mathbf{V}) = \frac{1}{T_s} H_b(p) \tag{5}$$

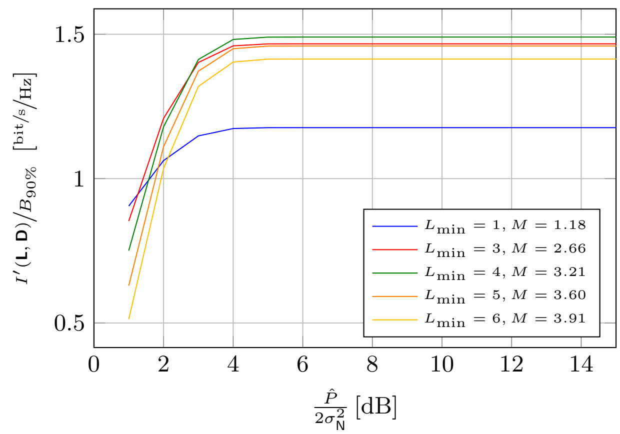

Fig. 2. Lower bound on the spectral efficiency for 1-bit quantized runlength modulated transmission with oversampling ratio $M = \frac{1}{T_s B_{90\%}}$

TABLE I
LINK BUDGET FOR TRANSMISSION OVER 140-220 GHZ WITH NLOS SCENARIO

Parameter	Value
Transmit and receive antenna gain	25 dBi
Path loss with one reflection (8-10m)	100-120 dB
Polarization mismatch	3 dB
Implementation loss	5 dB
Rx noise figure	10 dB
Rx temperature	350 K
Target SNR	10 dB
Transmit power	5-25 dBm

where $H_b(\cdot)$ is the binary entropy function and p is the sample flipping probability

$$p = \frac{1}{2}\left(1 - \operatorname{erf}\left(\sqrt{\frac{\hat{P}}{2\sigma_{\mathsf{N}}^2}}\right)\right). \tag{6}$$

The expression in (5) converges to zero for $(\hat{P}/2\sigma_{\mathsf{N}}^2) \to \infty$. The runlength coding reduces the effective (two-sided) bandwidth B of the communication system, such that $B < \frac{1}{T_s}$. The spectrum of a maxentropic runlength limited sequence is given in [7]. Without a maximum runlength constraint and for a triangular transmission pulse it is

$$S(\omega) = \frac{T_s^2 \sin^2\left(\frac{\omega T_s}{2}\right)}{(\tilde{\mu}+L_{\text{min}})\left(\frac{\omega T_s}{2}\right)^4} \frac{1 - \left|\frac{\exp(jL_{\text{min}}\omega T_s)}{\lambda^{L_{\text{min}}-1}(\lambda - \exp(j\omega T_s))}\right|^2}{\left|1 + \frac{\exp(jL_{\text{min}}\omega T_s)}{\lambda^{L_{\text{min}}-1}(\lambda - \exp(j\omega T_s))}\right|^2} \tag{7}$$

where $\lambda = \frac{\tilde{\mu}}{(\tilde{\mu}+1)}$ and $\tilde{\mu}$ is chosen s.t. $(\tilde{\mu}+1)^{L_{\text{min}}-1} - \tilde{\mu}^{L_{\text{min}}} = 0$, which maximizes (3) for a given L_{min}. By numerically computing the 90%-power-containment bandwidth $B_{90\%}$ of (7), the results in Fig. 2 for the spectral efficiency $I'(\mathsf{L},\mathsf{D})/B_{90\%}$ are obtained. It can be seen that oversampling w.r.t. to $B_{90\%}$ significantly increases the spectral efficiencies above 1 [bit/s/Hz], although no amplitude information can be resolved at the receiver. This proves the concept valuable for high-speed communication with constraints on the energy consumption.

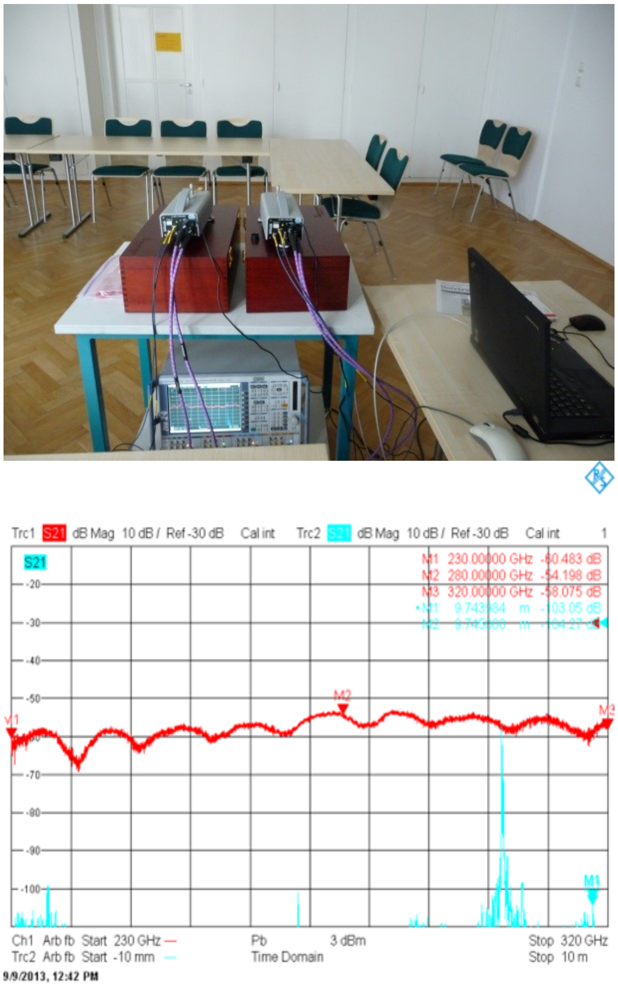

Fig. 3. Experiment setup (top) and impulse and frequency response after the reflection off wooden cabinet (bottom)

III. Channel measurements and RF Frontend

In order to achieve high-speed communication with data rates up to 1 Tbps, a large amount of bandwidth is required. The millimeter wave frequency range beyond 100 GHz offers these bandwidths. Especially the frequency range around 250 GHz is promising, since the average atmospheric attenuation is approximately 0.002 dB/m [8]. This value can be considered negligible for short range communication. Initial channel measurements in the frequency range from 230 GHz to 320 GHz have been carried out with a frequency range extended network analyser. Each frequency extender was connected to a horn antenna with a gain of approximate 20 dBi. The system was properly calibrated with the Thru, Reflect, Line method without the antennas before the measurement was performed. One representative measurement setup, the frequency response and calculated impulse response of the channel is shown in Fig. 3. For the non-line of sight (NLOS) scenario in Fig. 3, depending on the reflection path, an attenuation of 55 dB is observed at a distance of 8 m. The link budget for an NLOS scenario (one bounce off a wooden cabinet) is calculated and is presented in Table I. In contrast to the setup used for this channel characterization, a wireless system for high speed short-range communication will be integrated. Therefore, the necessary antennas for this kind of communication are assumed to be integrated in order to prevent connection parasitics. Moreover, they have to be broadband and achieve sufficient gain.

A promising approach can be found in multiple stacked Vivaldi-shaped open slot antennas: Compared to a typical relative bandwidth of about 15%, this concept offers bandwidths of more than 40% in respect to a center frequency of e.g. 180 GHz for a silicon-integrated antenna, see Fig. 4, Fig. 5 and [9]. Besides the high bandwidth required, a sufficient gain is necessary to deal with the losses (e.g. free space loss) associated with the frequency band in use. A typical gain value for this kind of integrated antenna is about 4 dBi at 200 GHz [9]. To overcome the limitations of single antenna systems and increase the gain available, antenna arrays are to be used. As an additional benefit, arrays introduce beam switching capabilities for communication with multiple nodes such as spatially distributed antennas in a MIMO setup or in board-to-board communications.

To ensure a proper phase relation between the single antenna elements of the array and achieve a high energy efficiency, more sophisticated concepts than active phase shifters for exciting the antenna array need to be investigated. The adaptive phase shifters usually being used in beam steering networks are complicated in design and are yet to be thoroughly researched for the required high frequencies. Moreover, they are demanding in terms of energy, since active devices are involved.

One approach is a passive distribution network in the shape of a Butler Matrix: Besides the higher energy efficiency due to the avoidance of active devices, Butler Matrices offer a discrete set of beams to be switched by simply addressing different input ports. Due to their inherent reciprocity, the same Butler Matrix can be used for the receive and transmit case. An example design using a 1x4 antenna array working in the millimeter wave range is given in Fig. 6. For very

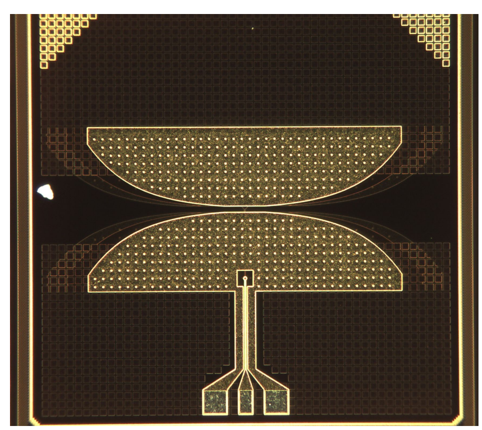

Fig. 4. Multiple stacked Vivaldi-shaped open slot antenna, fabricated in IHP SG13 process [10].

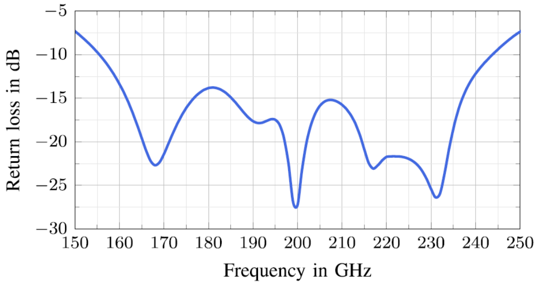

Fig. 5. Input reflection coefficient of antenna shown in Fig. 4 and further investigated in [9].

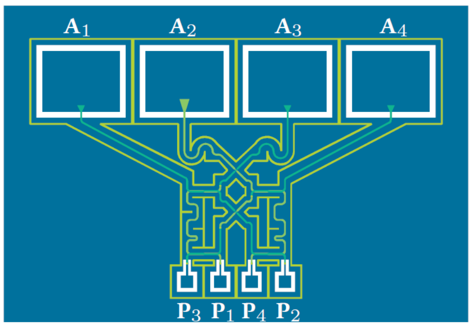

Fig. 6. Layout of Butler matrix with four input ports P (bottom) connecting a 1x4 antenna array of four patch antennas A (top).

broadband transmission, instead of the conventional approach of using LNAs, broadband and distributed concepts such as the Traveling Wave Amplifier need to be considered. Using systems like these, bandwidths of more than 100 GHz can be achieved easily already today [11]. However, the noise performance of these systems still needs to be addressed.

All parts of the RF frontend such as amplifiers and mixers need to be integrated close to the antenna in order to prevent high losses due to transmission lines and effects of connection parasitics. This strongly suggests the complete integration of the overall system into one package. For maintaining high system performance, usage of a heterogeneous technology platform is crucial: Most of the active circuitry needs to be fabricated in conventional silicon or CMOS processes, whereas especially the RF frontend (antennas, distribution networks) benefits a lot from being fabricated in an appropriate technology. Conventional semiconductor materials show a very high relative permittivity and associated losses (e.g. due to radiation into the substrate). For further enhancement of the performance of the antenna and distribution network, it is feasible to use a proper material platform showing low permittivity and loss in the desired frequency range, such as Benzocyclobutene [12]. The antennas need to be integrated on top of the overall package, to ensure proper radiation characteristics. An integration like this could be realized in a Back-end-of-line-process, layering the RF performant layers on top of the metal stack of e.g. a CMOS chip and allowing for short inter-layer connections in the stack.

To push the available system bandwidth even further or to relax the performance requirements of the single elements, MIMO systems can be taken into consideration. This could be realized by putting lots of high bandwidth transceivers consisting of very broadband antennas, distribution networks and amplifiers as stated above in parallel. By doing so and using the beam switching capabilities of the antennas and their distribution networks, one can achieve a full duplex node-to-node communication.

IV. Conclusion

Ways to enable energy-efficient wireless communication with data rates towards Tbit/s have been discussed. Those are coarse quantization and oversampling at the A/D-conversion as well as efficient design and integration of the RF components. As a numerical example, consider a system with a carrier frequency of 180 GHz. With the above mentioned Vivaldi-shaped open slot antennas a bandwidth of 40 % of the carrier frequency can be achieved yielding a bandwidth of 72GHz. With the results in Fig. 2 this allows to transmit approximately 108 Gbit/s. Using complex baseband signals and two polarization domains already increases this to an achievable data rate of 432Gbit/s, with even higher rates achievable using MIMO systems. This clearly shows the path towards Tbit/s wireless.

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