

Why Is White Noise Not Enough? Using Radio Front-End Models While Designing 6G PHY

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Abstract — Each subsequent generation of wireless standards imposes stricter spectral and energy efficiency demands. So far, layered wireless transceiver architectures have been used, allowing for instance to separate channel decoding algorithms from the front-end design. Such an approach may need to be reconsidered in the upcoming 6G era. Especially hardware-originated distortions have to be taken into account while designing other layer algorithms, as high throughput and energy efficiency requirements will push these devices to their limits, revealing their non-linear characteristics. In such a context, this paper will shed some light on the new degrees of freedom enjoyed while cross-layer designing as well as controlling multicarrier and multiantenna transceivers in 6G systems.

Keywords — 6G, cross-layer design, front-end nonlinearity.

1. Introduction

The increasing numbers of users and applications result in more demanding requirements being faced by wireless networks. This can be solved by densification of 5G network base stations, applying spectral efficiency improvement techniques and increasing the bandwidth utilized. However, this leads to higher costs caused by increased amounts of energy consumed by wireless transceivers, e.g. due to a higher number of radio front-ends (antennas) and more complex signal processing procedures both at the transmitter and the receiver. Therefore, the next generation (6G) technology will need to define new design paradigms to account for the increasing rising needs and new constraints.

Until now, research focused primarily on obtaining maximum spectral efficiency for a “perfect” radio front-end. However, while pushing the transceiver design towards its spectral and energy consumption limits, new phenomena become apparent and need to be taken into account. This can be analyzed using a typical wireless transmitter diagram shown in Fig. 1. In most cases, each of the depicted blocks, i.e. the modulator or the battery, is designed independently as a stand-alone unit. The dashed line shows typical splits between design domains. Most researchers, e.g. those specializing in radio resource management, assume a perfect and linear model of electronic components constituting the radio front-end (e.g. power amplifiers – PAs). In reality, however, a linear increase

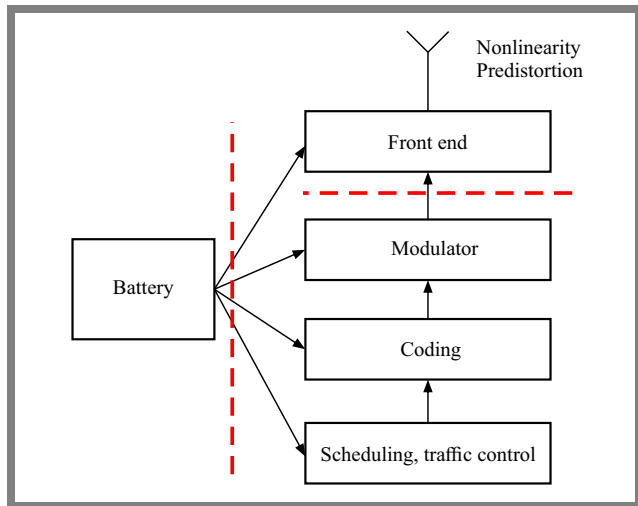


Fig. 1. Block diagram of a typical wireless transmitter – dashed lines indicate typical splits between separate design domains.

of the mean transmit power results in a linear increase of the amount of energy consumed and no signal distortion is achieved only when the difference between the clipping level and the mean transmit power (high back-off) is used. Unfortunately, such a front-end model concept cannot be used while designing highly energy-efficient systems. In a wireless system operating close to its energy efficiency maximum, non-linearity of the front-end characteristics and its influence on numerous system quality metrics has to be considered. For example, for a given PA, a higher transmission power results in an increased self-interference power generated both in the transmission channel and outside the transmission band, thus widening the system’s bandwidth and possibly decreasing its spectral efficiency [1]. At the same time, the transmitted signal, as a result of PA nonlinear characteristics, has its distribution changed, resulting in a nonlinear increase in power consumption [2]. These problems with nonlinear behavior can be extended to some other components of the wireless transceiver, e.g., analog-to-digital converters (ADCs) or batteries that power the front-end. As such, nonlinear front-end models should be considered while designing specific solutions for wireless transceivers and systems. This paper presents a couple of new approaches that can be utilized in multiple components of a future 6G system.

2. Optimization of PA Operating Point for the OFDM Signal

The operating point of a PA transmitting an orthogonal frequency division multiplexing (OFDM) waveform signal can be optimized in order to maximize total link spectral or energy efficiency [3]. Usually, the operating point is adjusted in order to achieve a given spectral emission mask (for the out-of-band frequency region) or error vector magnitude (EVM) (in the in-band region) at the transmitter's output. However, if the operating point is adjusted in order to maximize the link's spectral efficiency, significant gains in comparison to contemporary solutions are possible. This requires fine modeling of the transmitted signal waveform (in most cases its amplitude distribution is sufficient) and modeling of front-end non-linearity, in addition to such standard phenomena as multipath fading or interference observed at the receiver's input. If the target is to maximize energy efficiency, additional energy consumption models are required. This obviously depends on a given implementation, e.g. the PA class used, the type of modules utilized, and even the kind of coding relied upon.

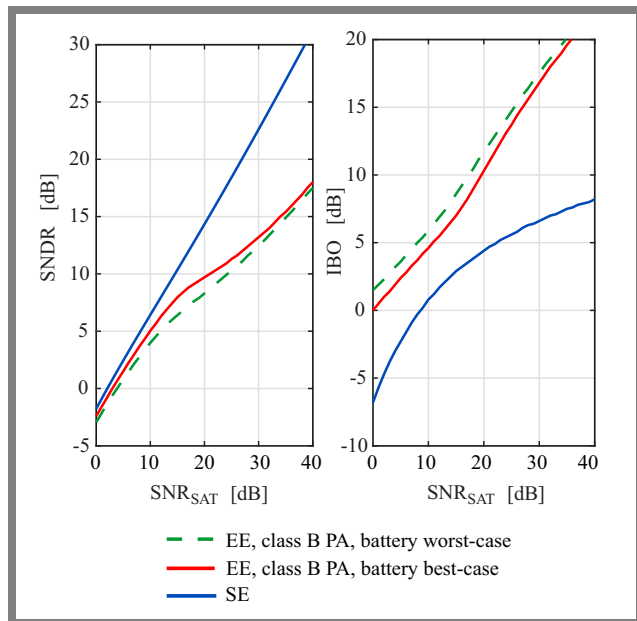


Fig. 2. Optimal values of signal-to-noise and distortion ratio (SNDR) and input back-off (IBO) as a function of saturation signal-to-noise ratio (SNR) as a result of spectral efficiency (SE) or energy efficiency (EE) maximization for two battery models.

While energy efficiency is the most important aspect for battery-powered devices, battery models are typically omitted while designing communications systems. In reality, a battery can reveal significant non-linear characteristics. For instance, the so-called “rate-capacity” effect results in instantaneous power required by the power amplifier being twice as high during transmission, which results in a more than two-fold increase in the amount of energy drained. All these models need to be combined together in order to identify the optimal PA operating point.

An example of solution based on the mathematical framework provided in [3] is shown in Fig. 2. It is assumed that the transmitter uses a soft-limiter class B PA. The operating point of the PA, i.e. IBO, is tuned in order to achieve maximum spectral efficiency (SE) or energy efficiency (EE). Furthermore, two different battery models are considered. The maximum unclipped PA output level is assumed to be 100 mW and the constant power consumption of other electronic components in the transmitter is set to 10 mW. SNR_{SAT} denotes the maximum signal-to-noise ratio achievable over a given link, i.e. when transmitting a single carrier with the power of 100 mW.

As expected, SE maximization achieves the highest signal-to-noise and distortion ratio (SNDR) in the entire SNR range. It should be noted that the optimal IBO value changes with the channel conditions. If EE is to be optimized, there is no point in achieving such a high SNDR, as it causes higher energy consumption, resulting in different SNDR and optimal IBO curves. Finally, the battery model should be considered while optimizing the EE parameter of a transmitter, as it exerts influence both on SNDR and optimal IBO metrics.

3. Front-end Characteristics Enabling Optimization of Non-Gaussian Waveform

While in most OFDM applications a large number of occupied subcarriers is considered, here the central limit theorem can be used to model instantaneous OFDM signal amplitude using Rayleigh distribution. However, if a small number of subcarriers is used, e.g. in the uplink from IoT devices, the above-mentioned distribution is not valid. Such a system relying on orthogonal frequency-division multiple access (OFDMA) is considered in future 5G and 6G systems in the scope of massive machine-type communications (mMTC), where large numbers of simple devices can connect to a base station for transmitting small amounts of data.

Optimization of the PA's operating point, together with the number of utilized subcarriers influencing complex envelope power variations, creates additional issues related to optimization of such a sensor network. The more subcarriers are used, the higher instantaneous power variations may be expected, resulting in a higher number of non-linear distortions. Moreover, a wider spectrum enables higher data throughputs. Therefore, optimization of the operating point in such a scenario is not easy. The frequency domain characteristic of non-linear distortion may be considered while designing subcarrier allocation procedures. While the nature of OFDM guarantees that subcarriers are orthogonal, the spectral regrowth caused by a non-linear PA means that users utilize adjacent frequency channels, causing mutual distortion. This noise-like effect will appear, contributing to multiuser interference, with its level depending on the frequency distance from the subcarriers used by the source of interference. From the resource allocation point of view, such an additional interference will play a significant role in the allocation of subcarriers to different users, as it may degrade the quality of transmission in adjacent sets of resources. Thus,

alternatives in the form of reducing the number of allocated subcarriers, which typically offer a lower distortion level or an improved link budget, or introducing some null subcarriers in the form of guard bands, should be considered.

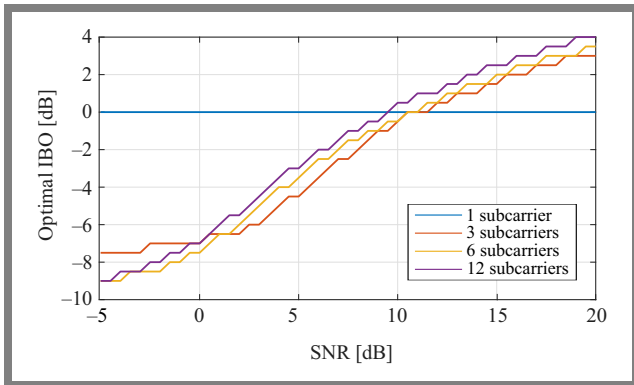


Fig. 3. Optimal operation point of the PA (in terms of data rate maximization) vs. the expected SNR with a low number of subcarriers used in the OFDM transmission.

In Fig. 3, we show an example of an optimal input back-off (IBO) of the PA (maximizing the data rate), as a function of the link’s signal-to-noise ratio (SNR) and the number of utilized subcarriers (from 1 to 12). The clipper/soft-limiter PA model is used. IBO is a ratio between the maximum unclipped input power of the amplifier and the mean input signal power. For a single carrier transmission, it is reasonable to transmit signal with the maximum power achievable without introducing distortion, i.e. 0 dB IBO, as the signal has a constant envelope. For a higher number of subcarriers, it is visible that a greater optimal IBO gives a higher SNR. Low IBO usage in this case will produce a higher desired signal power, but will also result in a significantly increased distortion power at the receiver. Note that the presented curves differ with the number of subcarriers, showing that there is a new degree of freedom in the optimization of IoT devices.

4. Front-end Aware Massive MIMO System

Massive MIMO (mMIMO) is currently a hot topic in fifth generation wireless networks, and the plans assume that it will be employed in subsequent generations as well. While it is commonly combined with OFDM, it inherits a similar non-linearity response. However, currently, in addition to spectral regrowth, unequal spatial distribution of the non-linear distortion is revealed as well. The nature of mMIMO causes the signals transmitted from each array’s antenna to merge (in-phase, boosting the power receives at a given location or in counter-phase, causing the fading of signals, depending on the type of precoding used). When the non-linearities generated and transmitted by each front-end component come into play, their addition has to be considered as well.

While it was believed that non-linear distortions will distribute omnidirectionally [4], there are some cases involving line-of-sight propagation or a low number of layers, when non-linear distortions have the same spatial distribution as

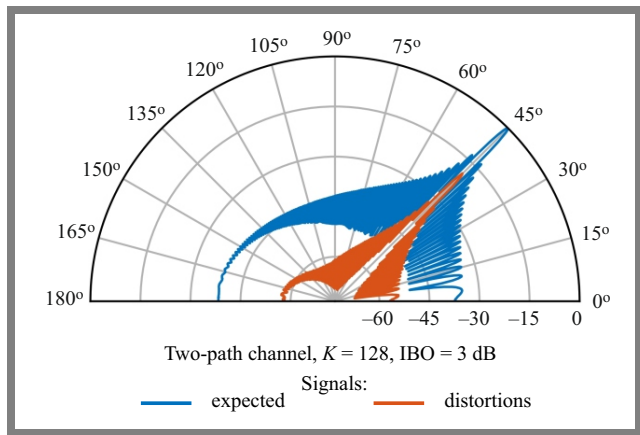


Fig. 4. Normalized radiation pattern of desired and distortion signal components in regard to azimuth angle for a two-path channel model, MRT precoding for the azimuth of 45°, 128 antennas and IBO = 3 dB.

the desired signal [5]. An example is shown in Fig. 4, depicting a normalized radiation pattern of an OFDM waveform radiated from 128 transmitters. In each transmitter, the same PA model, i.e. a soft-limiter of 3 dB IBO is used. Maximal ratio transmission (MRT) precoding for the azimuth of 45° is assumed. It may be noticed that both the desired signal and the distortion have similar spatial characteristics. In other words, in this case, the increase in the number of antennas does not influence the signal-to-distortion ratio (SDR). Obviously, this depends on the properties of the wireless channel. The SDR value at the scheduled receiver for 3 different number of antennas, 2 types of channels [6] and varying IBO levels is depicted in Fig. 2. As expected, SDR rises with IBO in all of the cases considered. Array gain is the most crucial parameter for the massive MIMO scenario. If full array gain is available only for the wanted signal, it is expected that SDR increases by approximately 12 dB by changing the number of antennas from 1 to 16. However, while it reaches 9 dB for the NLOS channel, it is lower than 5 dB for the LOS case. This shows that increasing the number of antennas will not solve the massive MIMO non-linear front-end problem.

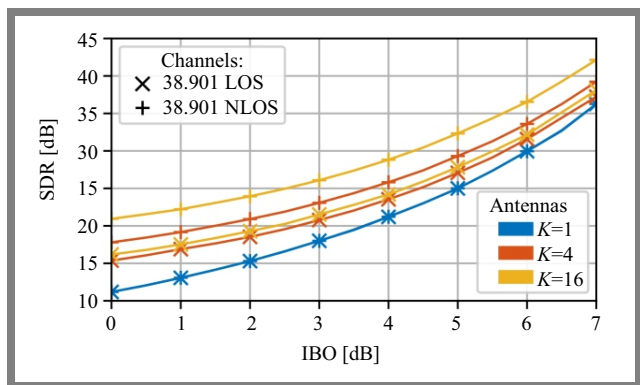


Fig. 5. SDR as a function of IBO for 3GPP channel models and varying number of K antennas with MRT precoding for the azimuth of 45°.

The massive MIMO technology is capable of solving issues with high path loss or multi-user interference, for instance. However, non-linear distortion still needs to be addressed.

This could be done using selected OFDM-typical methods, such as peak-to-average power ratio (PAPR) reduction algorithms [7] or by incorporating front-end predistortion. However, it is also possible to utilize some mMIMO-specific solutions, e.g. precoding that reduces non-linearity [8]. Unfortunately, while the method given in [8] is designed for a single carrier system, an mMIMO precoding that would be aware of OFDM processing is still missing. Obviously, the problem of non-linearity can be addressed at the other side of the link as well by utilizing advanced receivers. It has been shown in [9] that for a single antenna OFDM system, non-linear distortion may be treated as a kind of redundancy coding, distributing information from a given subcarrier to other subcarriers, thus increasing frequency diversity. Extension of the work described in [9] to a mMIMO system is an open topic as well.

5. Front-end Modeling for ML-based Network Optimization

The utilization of front-end characteristics may extend far beyond link-level optimization, providing new degrees of design freedom. The phenomenon of non-linearity should be considered while analyzing 5G and future wireless solutions on a system level. In this context, especially in a complex solution composed of multiple transmit antennas, multiple base stations that interfere with each other, and utilizing multistage processing, i.e. some proprietary traffic steering or scheduling algorithms, control and optimization are complicated. In such a case, no analytical models are available or they are highly simplified. Furthermore, we cannot rely on standard optimization methods. It has to be noted, however, that 6G systems are expected to move towards the utilization of machine learning (ML) and artificial intelligence (AI) in order to optimize network parameters based on the analysis of real data [10].

In this context, the most straightforward approach is to optimize the operating point of the PAs used at base stations. This parameter can be used to find a balance between the transmitted power, power amplifier efficiency, and nonlinear distortion level. Obviously, various objectives may be set, e.g. maximizing spectral efficiency, improving throughput of cell-edge users or maximizing energy efficiency. For reference, a classical method is proposed in [11], where the optimization of the PA's operation point is considered to achieve a maximum signal-to-noise and distortion power ratio in a single OFDM link. While the authors proposed an analytical solution, the model considered was relatively simple, i.e. only flat fading was taken into account. This is one of the reasons why this solution cannot be considered optimal. Therefore, we propose to utilize an augmented learning technique where, depending on the state of the network (which can be modeled in various ways, initially we resort to the users' path-losses), various PA operating points are considered, and by the optimal operating point is determined based on the network throughput metric.

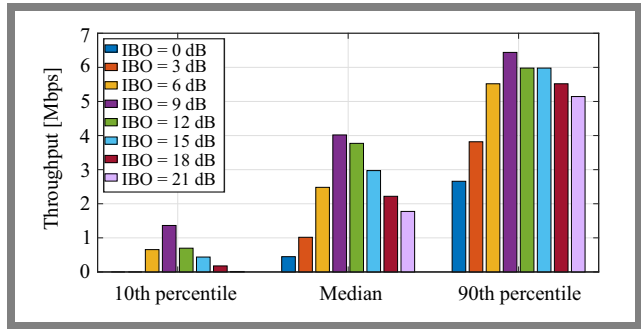


Fig. 6. Throughput of cell-edge (10th percentile), median, and the best (90th percentile) users obtained over the training epoch for different values of IBO.

We have evaluated the proposed solution by performing computer simulations. In the scenario considered, we researched a downlink in a single mMIMO cell with one BS equipped with a rectangular antenna array made up of 128 elements and operating at a center frequency of 3.6 GHz with a bandwidth of 25 MHz. Due to the low complexity of both hardware and signal processing, we have considered analog beamforming with the so-called equal gain transmission (EGT) precoder [12]. This type of precoder ensures that equal power is allocated to the BS's antennas. The PA installed at the BS, along with its non-linear effects, is modeled as a soft limiter [1]. We used the Wireless Insite RayTracing software to generate accurate radio channel coefficients for 150 sets of 20 pieces of user equipment (UE) distributed uniformly over the cell's area. A single set is referred to as a step, while all sets constitute an epoch. Throughout multiple epochs, the RL agent was applying different values of IBO (constant over the entire epoch), and related user throughputs were observed as rewards. The results are shown in Fig. 6. It is clearly visible that there exists an optimal value of IBO = 9 dB for cell-edge users (10th percentile), median users, and the best users (90th percentile). This value provides the best balance between the users' received power and non-linear distortion. A choice of IBO that is too close to the PA saturation point (0 dB, 3 dB, and 6 dB) reduces user throughput due to the high non-linear distortion level. On the other hand, for high values of IBO, the received power is too low. This phenomenon is clearly visible at the cell's edge users (10th percentile). From this point of view, ML models may be further trained to adjust IBO in a context-dependent manner, i.e. based on the users' path-loss distribution or potential location-related information.

6. Conclusions

The discussion presented above sheds some light on the typically overlooked problem of non-linearities present in wireless transceivers. Typical analytical models resorting to white noise and multipath fading channels cannot be used if the design is focused on an ultimately efficient 6G system. However, this requires a significant effort in realistic modeling and optimization of the wireless front-end, while designing higher-layer algorithms. Such an approach will provide a new degree of freedom, at the cost of increased complexity. One

potential solution is to support a classic convex optimization approach with machine learning tools.

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