The Case for All-Digital Beamforming at Millimeter Wave

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Abstract

Here we examine some of the tradeoffs of hybrid-beamforming systems and speculate that with the right device technology, we are on the verge of a back-to-the-future moment. Where system architects can directly extend their all-digital mass-MIMO AAS base station architecture to mmWave without the compromises and complexity of introducing hybrid RF beamformers.

INTRODUCTION

We are starting to see new all-digital beamforming architectures emerge that provide very high EIRP [1]. Here, we take a closer look at the challenges of hybrid beamforming and the benefits of all-digital beamforming and highlight a new Doherty amplifier that may tip-the-scales. Allowing base station suppliers to leverage their existing investment into all-digital Mass-MIMO AAS platforms and extend them for use at mmWave.

ALL-DIGITAL VS. HYBRID BEAMFORMING

It is natural for BTS manufacturers to first explore extending current sub-6GHz all-digital beamforming Mass-MIMO AAS platforms to mmWave. This preserves the basic architecture and more importantly, the advanced signal processing/algorithms needed to realize beamformed spatial multiplexing. However, due to the dramatic increase in channel bandwidths offered by mmWave and the need for many active channels, there is a valid concern that the power dissipation and cost of such a system would be prohibitive.

Therefore, many OEMs are exploring new Hybrid-beamformed architectures [2], which allows flexibility between the number of baseband channels to the number of active RF channels. However, there are significant compromises that are inherent with hybrid beamforming.

Hybrid Beamforming

It has been shown theoretically that hybrid beamforming can achieve the same sum-rate capacity as an all-digital beamforming system under certain conditions [3]. One of the key assumptions is that a shared-aperture or fully-connected beamformer is used. Fig. 1 shows the complexity of a 4 x 16 hybrid transmit array.

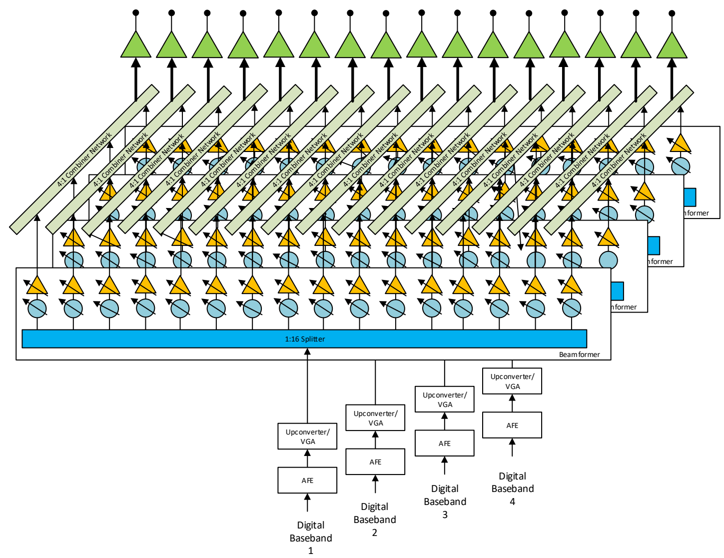

Fig. 1. Fully-connected Shared-aperture hybrid beamformer

The complexity of the phase shifter and variable gain network is well beyond the capability of core-beamformers being offered on the market today. To manage the complexity a sub-arrayed panel approach is being pursued as shown in Fig. 2.

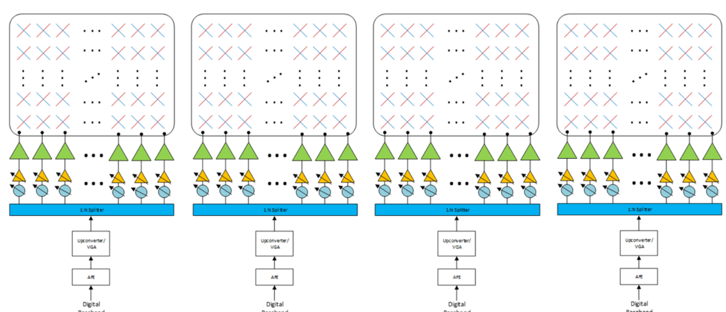

Fig. 2. Sub-array Paneled hybrid beamformer

In this suboptimal configuration, the number of phase shifters and variable gain blocks remain the same but the number of PA's (and LNAs for receive) increases four-fold!

This configuration can synthesize only a single beam per panel at any given time slot. This implies that if a handset can support only a 50MHz bandwidth but the base station support 400MHz bandwidth, then 88% of the capacity during that time slot will go unutilized. In contrast, a digital beamforming system can beamform independently across frequency and form a unique beam to many simultaneous users. The two scenarios are illustrated in Fig. 3 and Fig. 4.

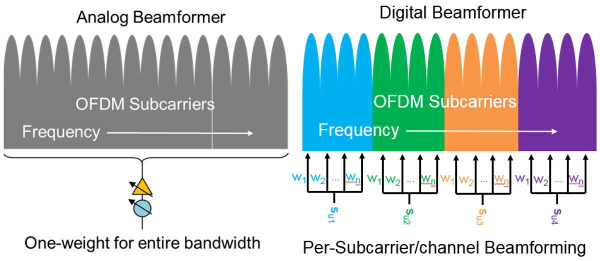

Fig. 3. Hybrid beamforming doesn't allow the frequency to be subdivided to different users during a timeslot

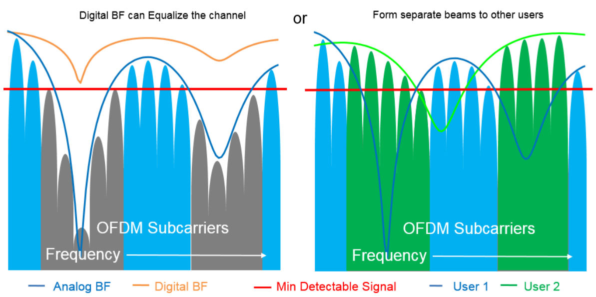

Fig. 4. In frequency selective conditions, all-digital beamforming systems can fully utilize the channel

Another critical aspect of hybrid beamforming is that it inhibits the use of digital predistortion. All sub-6GHz base stations use digital predistortion (DPD) and Doherty PAs to maximize efficiency and linearity. As shown in Fig. 5, DPD always has a 1:1 relationship with the PAs because every PA is slightly different and DPD coefficients are adaptively tuned and maintained for each.

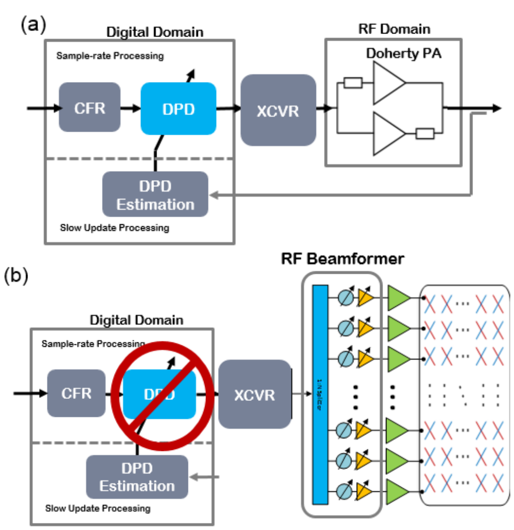

Fig. 5. (a) 1:1 mapping of baseband DPD and Doherty PA; (b) shows that DPD is not effective in a 1:N analog beamforming configuration

It remains an open research problem to determine how effective DPD can be in 1:N configurations. The problem depends not only on how well matched each PA is but also stable the load each PA is seeing. In phased arrays, as the beam is scanned, the loading changes, making the problem more challenging.

Until this problem is solved, hybrid beamforming systems will need to rely on low-efficiency linear PAs. Depending on EVM and back off conditions the PAE can be as low as 5% for high-QAM 5G NR signals.

All-digital Beamforming Power Consumption

The first concern with all-digital beamforming architectures is that the power dissipation for the needed EIRPs will exceed the thermal capacity of the heat-sink and require forced air cooling (i.e. fans). Due to maintenance and lingering reliability concerns, forced-air systems are discouraged by most operators.

As a baseline to understanding the power dissipation of an all-digital beamforming system, it is useful to analyze a base station targeting an EIRP of 65 dBm using off-the-shelf component. In most cases, these components were developed for point-to-point radio applications and have been available for years.

A key assumption we need to start is the antenna gain. It is common for terrestrial cellular antennas to provide at least 14dBi of gain using a 12° x 120° sectorized antenna. Given the tower heights and coverage goals are unchanged, a similar sectorized antenna can be designed at mmWave. Although it will be much more compact and allows integration with the RF electronics. Next, we select a high-power 28GHz GaN balanced-amplifier like the TGA2595.

The multi-slat array and transceiver line-up are shown in Fig. 6. Accounting for 1.5dB of circulator- and feed-losses the power at the antenna port is 27dBm. To achieve 65dBm EIRP we need 16-transceivers that together provide 12dB of digital beamforming gain.

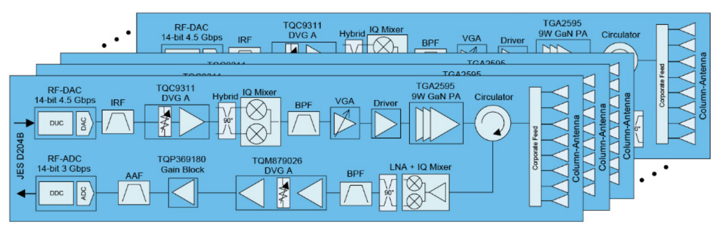

Fig. 6. High Power All-Digital Beamforming AAS – Using Todays Off-the-shelf Components

The power consumption for each transceiver is shown in Fig. 7. It follows, that the total power dissipation (P_{DISS}), at 80% transmit duty cycle for all 16-slats, will be 220W/polarization and a dual-polarized system would require 440W. As usual, the PA dominates the power dissipation budget.

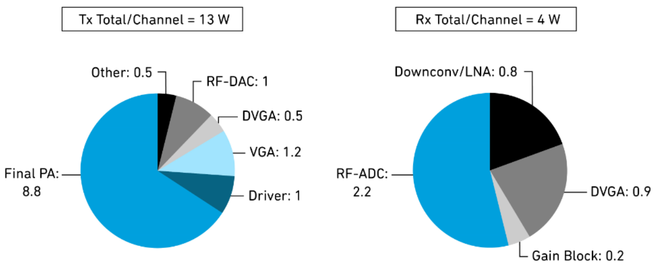

Fig. 7. Power Dissipation Budget of TX and RX Chains

For all outdoor tower-top electronics where passive cooling is required, it is challenging to thermally manage more than 300W from the RF subsystem. Therefore, an all-digital beamforming architecture using today's off-the-shelf components seems prohibitive.

However, new GaN front-end modules are on the horizon to help address this. As shown in Fig. 8, these new PAs extend the tried-and-true Doherty efficiency-boosting techniques to mmWave.

Performance estimates of a 40dBm P_{SAT} symmetric multi-stage Doherty predict PA power dissipation can be reduced more than 50%. This improvement alone, in the above system, drops the total P_{DISS} below 300W.

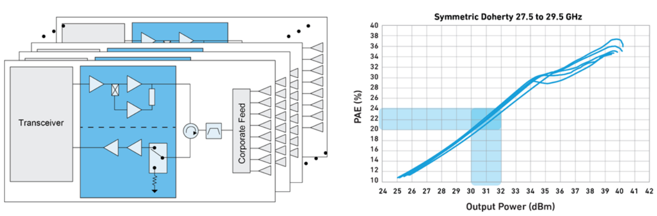

Fig. 8. mmWave GaN Doherty and Low-Noise Switch-LNA Front-End Module

Combined with power savings from next-generation RF-sampling DACs/ADCs, advancement in mmWave CMOS transceivers, and increased levels of small-signal integration it won't be long before we see more all-digital beamforming solutions in the market.

Conclusions

Hybrid beamforming architectures allow flexibility between the number of baseband and RF channels but there are many compromises compared to an all-digital approach. Using todays off-the-shelf components, the power dissipation of all-digital architectures seems prohibitive. New high power mmWave Doherty PAs along with advances in small-signal and CMOS transceivers may tip-the-scales back towards the all-digital approach.

References

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Acronyms

AAS: Active Antenna System
BTS: Base Transceiver Station
DPD: Digital Predistortion
EIRP: Effective Isotropic Radiated Power
EVM: Error Vector Magnitude
MIMO: Multiple Input Multiple Output
OEM: Original Equipment Manufacturer