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Low Power and Reduced Hardware UWB Beamformers for Future 5G Communications

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SUMMARY We present a novel hybrid beamforming architecture for high speed 5G technologies. The architecture combines several new concepts to achieve significant hardware and cost reduction for large antenna arrays. Specifically, we employ an on-site code division multiplexing scheme to group several antenna elements into a single analog-to-digital converter (ADC). This approach significantly reduces analog hardware and power requirements by a factor of 8 to 32. Additionally, we employ a novel analog frequency independent beamforming scheme to eliminate phase shifters altogether and allow for coherent combining at the analog front-end. This approach avoids traditional phase-shifter-based approaches typically associated with bulky and inefficient components. Preliminary analysis shows that for an array of 800 elements, as much as 97% reduction in cost and power is achieved using the hybrid beamformer as compared to conventional beamformer systems.
key words: *ultra-wideband, 5G, beamformer, arrays, frequency independent, self-mixing*

1. Introduction

With the growing interest for reduced size platforms, such as unmanned aerial vehicles (UAVs), and requirement for small ultra-wideband (UWB) performance to address multi-functionality and security, there is strong need for small UWB apertures and transceivers. The latter must be small, agile, low power and provide scanning across large instantaneous bandwidth apertures to enable increased spectral efficiency, spatial multiplexing, and simultaneous transmit and receive (STAR) applications. Furthermore, UWB arrays offer high data rates and allow for secure communication using long codes that spread across the bandwidth. With these capabilities, such transceivers can lead to the ultimate software radars/radios. They are also needed for secure communications with multiple input multiple output (MIMO) capabilities.

As is the case with all arrays, it is important to achieve low cost and low power beamforming. For UWB arrays, beamforming must be frequency independent [1]. However, to date, the development of low power wideband beamformers has been a challenge. In fact, traditional beamformers and MIMO radars have been mostly suited for narrowband or multiband operations with inherently high-power requirements. Depending on the level of intelligence, beamforming techniques can be classified into two major categories, namely digital and analog beamforming. Analog beamformers rely on phase shifters at the front-end to steer the beam. However, due to tuning limitations, they are only capable of beamforming in a single spatial direction at a time [2]. That is, beams from multiple directions cannot be formed simultaneously, limiting the capability of the analog beamformer, particularly for MIMO applications. Also, phase shifters suffer from high losses and bandwidth limitations. This issue is exacerbated for arrays with a large number of elements as a large number of phase shifters is required. As a result, traditional analog beamformers suffer from large size, weight, and complexity, not to mention power consumption. In addition, traditional analog beamformers have other drawbacks. Among them: 1) performance suffers from quantized levels of phase increments, 2) phase shifting networks imply large processing overhead, 3) significant hardware complexity that impacts size, power, and cost, and 4) do not accommodate spatial multiplexing.

The aforementioned pitfalls motivate us towards digital beamforming for UWB operations. Indeed, digital beamforming approaches offer more flexibility [1], [3]. In this case, beamforming and related adaptive algorithms are carried out at the digital back-end of the transceiver using field-programmable gate arrays (FPGAs) or other digital processing units. Digital adaptive beamformers can achieve more accurate main beams, null steering, side lobe level control, simultaneous multi-directional beams, and even spatial multiplexing. However, existing baseband digital beamformers have extensive hardware requirements as they employ separate analog-to-digital converters (ADCs) for each signal path, as illustrated in Fig. 1 (top). The large number of high-cost and power-hungry ADCs results in excessive power consumption in the back-end circuitry, making such approaches limited to small arrays. This reduces performance and transceiver efficiency, particularly for applications with limited space and power budgets, required for future small vehicular platforms.

Indeed, two bottlenecks exist in UWB communication: 1) narrow bandwidth for realizing the down-conversion process, and 2) highly expensive and power hungry digital beamsteering back-ends. With this in mind, we present a new beamforming concept for small high data rate platforms that overcomes the aforementioned complexity and large power requirements. Figure 1 depicts our novel hybrid transceiver and contrasts it to traditional beamformers. The proposed

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beamformer is referred to as On-Site Code Division Multiplexing (OS-CDM) and incorporates several features: a) UWB aperture fabricated via standard, low cost, Printed Circuit Board (PCB) techniques, b) co-integrated array feeding [4], [5], c) On-Site Code Division Multiplexing for hardware and power reduction [6], [7] (see Fig. 1 (bottom)), and d) a frequency independent receiver concept for beamforming (see Fig. 2). The proposed OS-CDM concept uses coding to combine many array element signals into a single ADC. As a result, cost and power reduction can be achieved. Further, back-end wiring/pins are also reduced since the entire composite signal (covering all bands) is pushed to the processing unit.

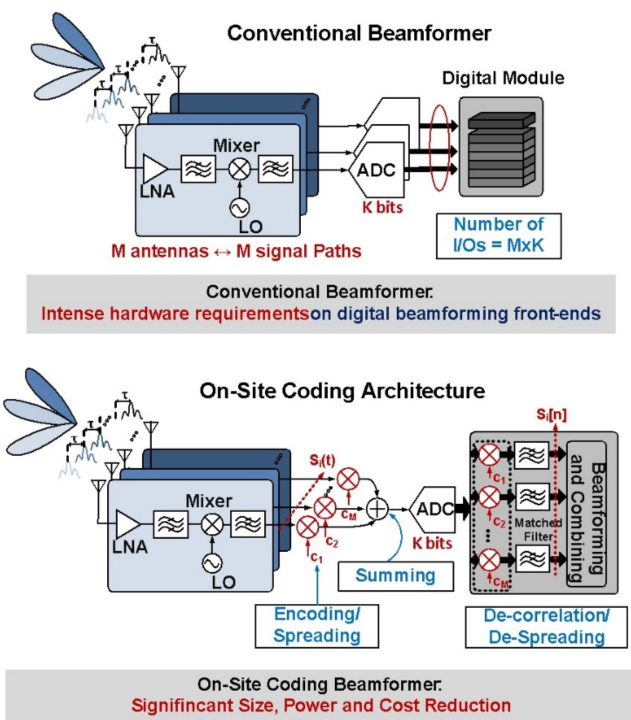

Fig. 1 Traditional beamformer using a single ADC for every antenna element (top) vs. the on-site coding scheme that uses one ADC to serve several antennas concurrently (bottom).

In this paper, for the first time, we combine OS-CDM with a novel frequency independent beamforming concept at the analog stage. This hybrid beamforming approach promises game-changing novelties for a new class of transceivers with significantly reduced power and hardware needs.

2. Receiver Architecture

As depicted in Fig. 2, the beamformer, presented in this paper, consists of three necessary components: a UWB antenna array, a frequency independent beamformer, and an OS-CDM concept for hardware reduction. This receiver architecture is suitable for UWB communications. To date, no such architecture exists to handle UWB beam steering with down-conversion at the baseband and across large bandwidths. Both technologies are required to realize practical UWB communications using the small form factor required for 5G communications.

2.1 Ultra-Wideband Tightly Coupled Array

A key component of the proposed wideband beamformer is its reduced size UWB antenna arrays. The latter offers high data rates and enable continuous operations across large bandwidths. Recently, a new class of UWB tightly coupled arrays with compact feeding networks [4], [5], [8]–[11] was designed and implemented to deliver more than 8:1 [8] and even 13:1 [5] of continuous bandwidths. Notably, these arrays are designed to achieve the fundamental bandwidth limits [9] for array design (see Fig. 4). Likewise, up to 6:1 bandwidth have been demonstrated while scanning down to 70° from broadside in all scan planes [10]. The architecture is based on tightly coupled dipole arrays (TCDA) with capacitive coupling that serves to cancel the ground plane's inductance [11]. As such, broadband impedance matching [1] and extremely low profile (i.e., The array thickness is only 1/16th of the wavelength at the lowest frequency of op-

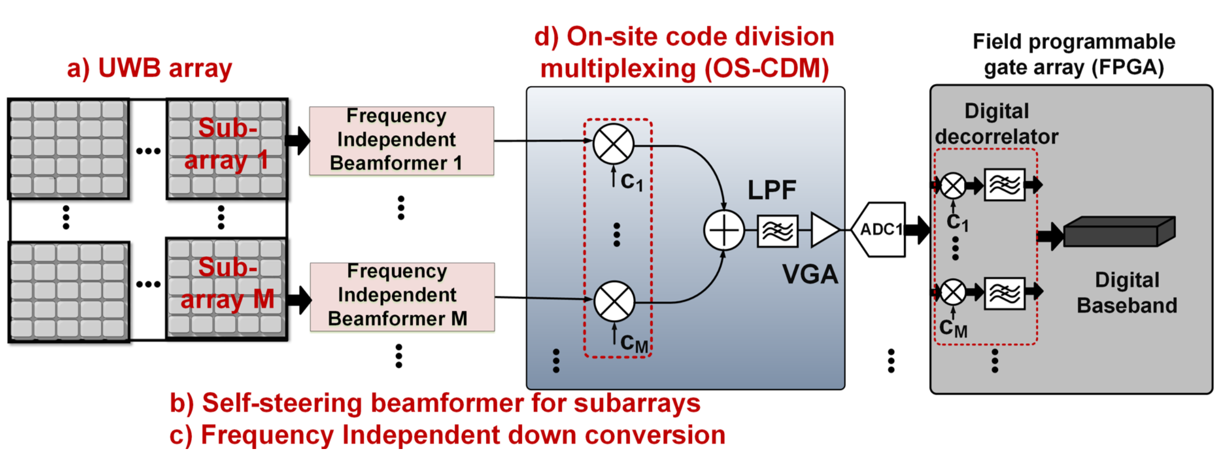

Fig. 2 Hybrid beamforming concept that combines the on-site code division multiplexing (OS-CDM) approach with subarrays for further reduction of costs in achieving frequency independent beamforming.

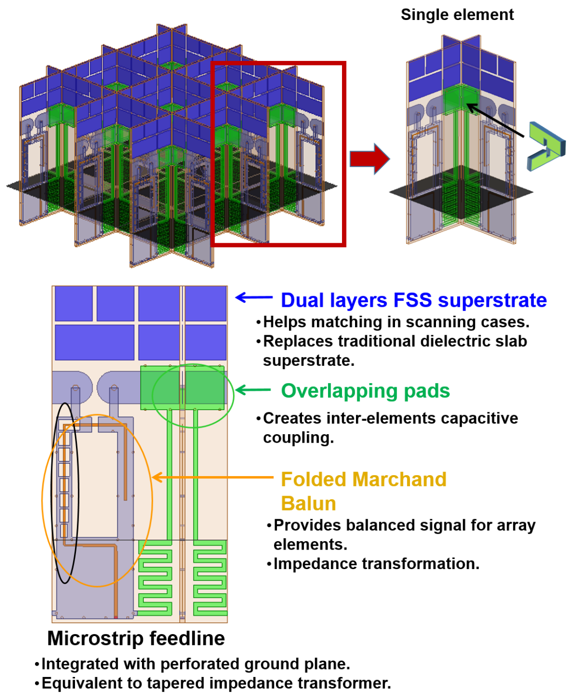

Fig. 3 Tightly coupled dipole array (TCDA) [4], [5], [8]–[11] rendering and details of the wideband feed structure. More than 9:1 bandwidth has been achieved by these conformal arrays. Also, the arrays are scalable from low MHz up to 90 GHz using PCB fabrication processes.

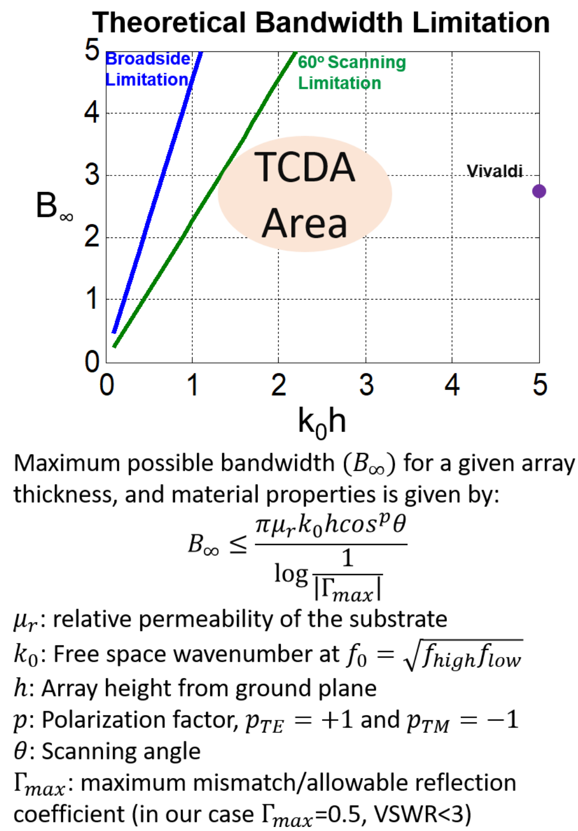

Fig. 4 Bandwidth limits of conformal antennas vs. thickness, h, and VSWR [9].

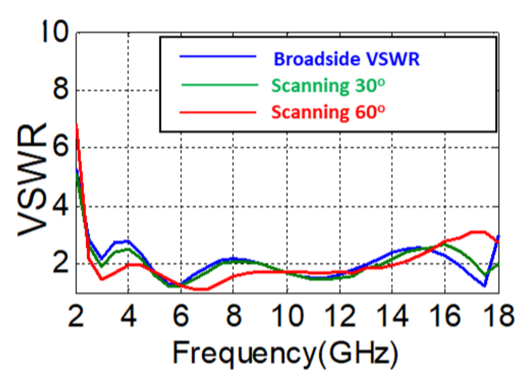

Fig. 5 VSWR of the array in Fig. 3 for different scan angles down to 60°.

eration) have been achieved. The geometrical details of each dipole and its feed are given in Fig. 3. As seen, the tightly coupled dipole is integrated with a folded Marchand balun serving as the feed and matching network. To enhance scanning performance to low angles, metallic periodic squares, forming a frequency selective surface (FSS), are placed on top of the array [10]. These FSS surfaces are lightweight and can be easily printed on the same board as the dipole array. Figure 5 shows the performance of the TCDA array with scanning down to 60° from boresight. The voltage standing wave ratio (VSWR) plots show excellent impedance matching across a 9:1 bandwidth while scanning.

2.2 On-Site Code Division Multiplexing

The benefits of the aforementioned array can only be realized when paired with a suitable beamforming back-end. As available beamformers are narrowband, on-site coding (see Fig. 1) is a game-changer in beamforming technology. A key aspect of this technique is the introduction of code division multiplexing (CDM) to identify the signal associated with each antenna array element. Using this coding approach, the signals from each array element can be summed and treated as a 'single integrated signal' prior to digitization. Thus, a single ADC can be used to serve many array elements. As such, power-hungry ADCs are significantly reduced and much hardware reduction is achieved as well. More importantly, once digitization is achieved, de-correlation can be applied to perform beamforming at the digital domain. This is done via software processing; hence multiple beams can be used to receive and/or transmit concurrently. This approach also removes the usual phase-tuning Voltage Controlled Oscillators (VCOs) with an array of mixers.

2.2.1 OS-CDM Cost and Power Reduction

Figure 1 depicts the block diagrams of a traditional digital beamformer and an on-site coding receiver beamformer. As can be seen, the RF front-end of the receiver section is identical for both architectures. As already mentioned, the main advantage of the on-site coding receiver is the use of a single ADC. This results in significant reduction in cost and power.

Considering real components, the comparison between these two architectures is given in Fig. 6. We note that evaluation boards with maximum ratings were considered for comparison. For the conventional system, the following components were considered: 1) ADC (AD9248) with sampling speed of 40 mega samples per second (MSPS) and 14-bit resolution [17], and 2) Virtex-7 FPGA (VC707 evaluation board) [18]. For the OS-CDM, the following components were used: 1) ADC (AD9250) with 250 MSPS sampling speed and 14-bit resolution [19], 2) Virtex-7 FPGA (VC707 evaluation board) [18], and 3) customized encoder board to perform on-site coding. As seen in Fig. 6, the OS-CDM consumes only 15% of the power and 20% of the cost for the conventional digital beamformer [7]. This existing low power and low cost beamformer can be extended to handle thousands of array elements in a systematic and frequency independent manner.

2.2.2 OS-CDM Signal Analysis

In our previous work [6], [7], [12], [15], [16], we have conducted extensive analysis to study the effect of OS-CDM on noise degradation. It was shown that using orthogonal codes, such as Walsh-Hadamard (WH) codes, no SNR degradation incurs for up to 8-elements per ADC. More in detail, in [6], [7], [12], various codes from a family of synchronous Walsh Hadamard codes and asynchronous Gold codes were studied, based on initial bit error rate (BER) optimization using different modulation schemes and 8 signal paths. For a highly synchronous system like OS-CDM, Walsh Hadamard codes proved to be ideal choice as they lead to smaller SNR degradation. Simulation results for 8 signal paths using WH and Gold codes (GC) for different modulation schemes, namely, binary phase shift keying (BPSK), Quadrature phase shift keying (QPSK), and 16-quadrature amplitude modulation (16-QAM). The BER curve was computed for each modulation scheme after coherently combining signals from all 8 signal paths. This curve was plotted and compared against the theoretical BER. The latter is shown in black in Fig. 7(a)–7(c).

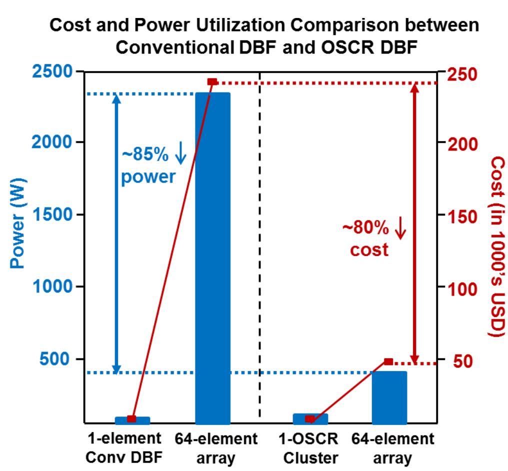

Fig. 6 Comparison between 64-element conventional beamformer and 64-element OS-CDM in terms of cost and power. 1-OS-CDM cluster corresponds to combining 8-paths together into a single path [7].

2.2.3 OS-CDM Hardware Fabrication and Testing

The OS-CDM has already been demonstrated (fabricated and tested) in [6], [7], [12], [13], showing an unprecedented factor of 8-fold hardware reduction in ADC count with corresponding reduction in power consumption. Also, it has been validated experimentally across 0.5–5 GHz. The backend electronics for the OS-CDM concept have also been fabricated and tested at low frequencies for 8 signal paths [6], [12], [13]. As illustrated in Fig. 8, OS-CDM has been implemented in the form of a multi-channel (2, 4, and 8 channels) receiver using commercial-off-the-shelf (COTS) components and PCB boards with integrated ADCs, mixers, low-noise amplifiers (LNAs) and FPGAs. Measurements were performed in an anechoic chamber using a UWB antenna array operating from 200 MHz to 2.5 GHz for multibeam tracking [13] at multiple frequencies. Results verified that on-site coding has minimal SNR degradation. Typical direction-finding accuracy was within 0.1 degree or so [7].

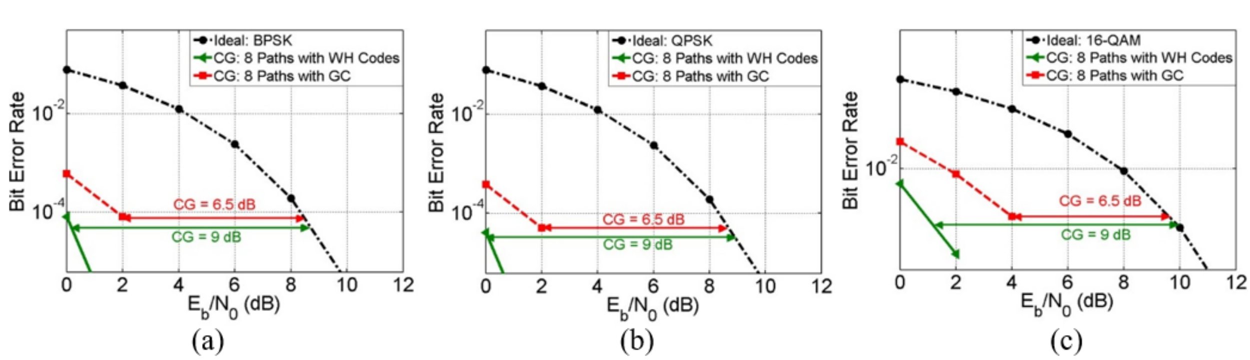

Fig. 7 BER analysis of an eight-channel OSCR for various modulation schemes when Walsh-Hadamard (WH) and Gold Codes (GC). The computer BER and combined gain (CG) are compared with theoretical limits for the same modulation scheme (shown in black): (a) BPSK, (b) QPSK, and (c) 16-QAM [7].

2.3 Frequency Independent Beamforming

The proposed OS-CDM/frequency independent beamformer with subarray segmentation is depicted in Figs. 2 and 9. That is, the frequency independent beamforming concept is applied at the front-end of the array, but only to a small groups of elements (subarrays). Subsequently, these groups are combined via on-site coding. This combined approach provides even more reduction in hardware and power without impacting beamforming resolution. Even more important, the hybrid beamformer concept is simple and easy to implement. Concurrently, it is beneficial for large and smaller antenna arrays. Its operation is as follows:

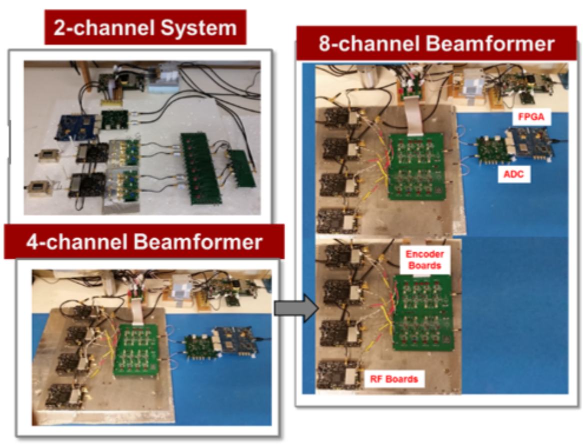

Fig. 8 Fabricated prototypes of 2, 4, and 8-channel OS-CDM receiver using a single ADC [6], [7], [12], [13].

1) The entire array is first segmented into small sub-apertures. These sub-apertures consist of arrays of 5×5 up to 25×25 elements, depending on design goals. Reconfiguration of the aperture size and group choice is done using switches placed behind each array element. That is, each antenna element is equipped with a monolithic microwave integrated circuit (MMIC) switch. Doing so, the beamwidth of the array can be controlled.

2) Using the concept of self-mixing and symmetrical phase cancellation, the subarray elements are summed in congruence to produce the beam without using any phase shifters. Only mixers are inserted to self-mix the signals from oppositely phased array elements. Fig. 9 shows one realization of this concept based on a recent patent [14].

More in detail, we assume an array of $2 \times n$ linearly and equally spaced elements, with d being the inter-element distance. We define n to be the set of non-zero integers determining the position of the elements in reference to the center. For instance, the n^{th} antenna element is identified by moving left or right from the center. The signal at the n^{th} element has a time delay equal to $\pm|n|\tau$, where τ is related to the angle of arrival (AoA) θ using,

$$\tau = d/c \sin\theta \tag{1}$$

In (1), c is the speed of light in free space. Hence, the relative phase between two successive elements is defined as,

$$\phi = 2\pi f_{RF} \tau \tag{2}$$

where f_{RF} is the RF signal frequency. The goal is to compensate for the phase delays at each antenna element to coherently combine the signals from all antenna elements and

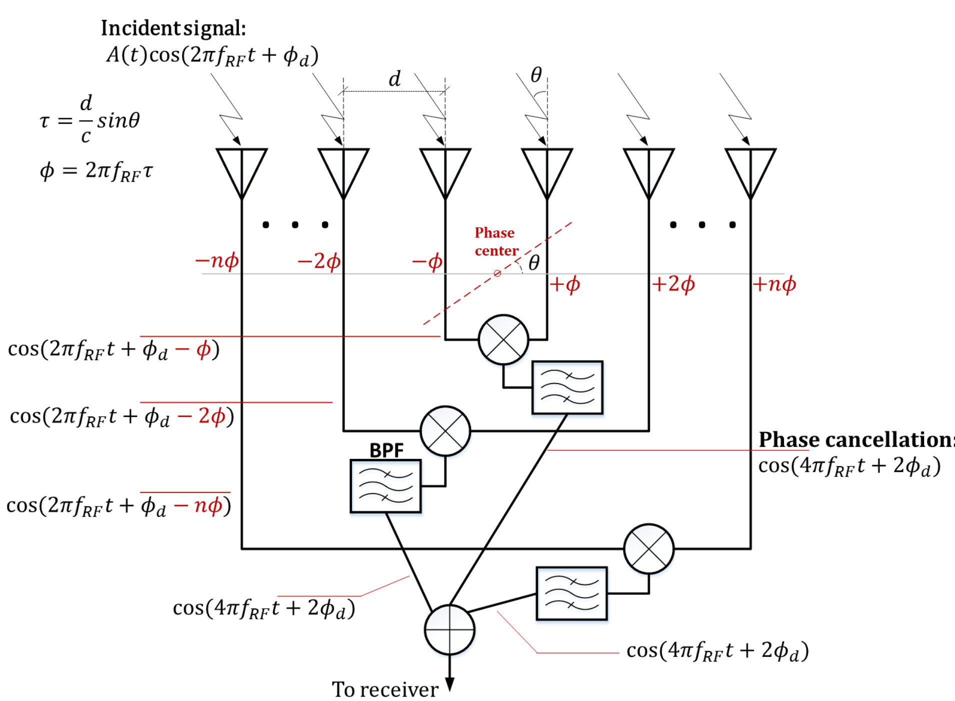

Fig. 9 Frequency independent beamforming for the subarrays shown in Fig. 2 [14].

Table 1 ADC requirements for various array sizes showing reduction in cost and power using the hybrid frequency independent/OS-CDM concept in Figs. 1, 2, 6, and 7. Notably, the data are the same at all operational frequencies as the RF front-end is scalable.

Array size	Sub-apertures size	Number of ADCs (conventional)	Number of ADCs (hybrid concept)	% reduction in Power	% reduction in Cost
800	100	800	8	97.51%	96.87%
200	25	800	8	90.05%	87.49%
64	8	64	1	96.11%	95.11%

maximize SNR.

As illustrated in Fig. 9, the phase center is chosen at the middle of the subarray. Doing so implies that oppositely spaced elements away from the center have an incremental phase delay of $\pm\phi$. This architecture is then employed to sum the signals with opposite phase and therefore cancel the time delays due to array element location. To verify this, we assume a quadrature amplitude modulation (QAM). Without accounting for the noise, the received signal at the n^{th} antenna element is,

$$s_{n;\pm|n|\tau}(t) = A(t\mp|n|\tau)cos(2\pi f_{RF}(t\mp|n|\tau)+\phi_d) \quad (3)$$

where $A(t)$ and ϕ_d are the modulation amplitude and phase, respectively.

Considering a narrowband signal and neglecting multipath fading, the delay can be considered much lower than the bit rate T_b, *viz.* $\tau << T_b$, hence,

$$A(t \mp |n|\tau) = A(t) \quad (4)$$

Replacing (4) into (3), the signal becomes,

$$s_{n;\pm|n|\tau}(t) = A(t)cos(2\pi f_{RF}(t \mp |n|\tau) + \phi_d) \quad (5)$$

Using (2), (5) can be rewritten as,

$$s_{n;\pm|n|\phi}(t) = A(t)cos(2\pi f_{RF}t \mp |n|\phi + \phi_d) \quad (6)$$

For $n = \pm1$,

$$s_{\pm1;\pm\phi}(t) = A(t)cos(2\pi f_{RF}t \mp \phi + \phi_d) \quad (7)$$

By mixing these two signals with opposite phase with each other, this yields:

$$\begin{aligned} s_{1;\phi}(t)s_{-1;-\phi}(t) &= A(t)cos(2\pi f_{RF}t - \phi + \phi_d) \quad (8)\\ &\times A(t)cos(2\pi f_{RF}t + \phi + \phi_d)\\ = 1/2A^2(t)(cos(2\phi) &+ cos(2\pi(2f_{RF})t + 2\phi_d)) \end{aligned}$$

In (8), up-conversion resulted in canceling out the phase delays $\pm\phi$. The signal product is then filtered out, resulting in having the information signal centered at twice the RF Frequency, with double the modulation phase,

$$s_{1;\phi}(t)s_{-1;-\phi}(t) = 1/2A^2(t)cos(2\pi(2f_{RF})t+2\phi_d) \quad (9)$$

Similarly, for $n = \pm2$, and proceeding with the same mixing and filtering approach, the result is

$$s_{2;2\phi}(t)s_{-2;-2\phi}(t) = 1/2A^2(t)cos(2\pi(2f_{RF})t + 2\phi_d) \quad (10)$$

Accordingly, the signals received at both n^{th} elements will be mixed together and filtered, such as,

$$s_{n;n\phi}(t)s_{-n;-n\phi}(t) = 1/2A^2(t)cos(2\pi(2f_{RF})t + 2\phi_d) \quad (11)$$

That is, the combined signal resulting from mixing signals with $\pm|n|\phi$ phase delayed signals, is

$$|n|/2A^2(t)cos(2\pi(2f_{RF})t + 2\phi_d) \quad (12)$$

By examining (12), it is clear that signals are coherently combined at this stage. Notably, signals from any direction will be equally well received. As a result, higher gain is exhibited in all directions. This implies high SNR for the received signal to be subsequently demodulated and decoded at the back-end. Clearly, because of the elimination of phase shifters, this beamformer is frequency independent and has a bandwidth equal to that of the antenna array.

3) To achieve directionality and reject unwanted signals, the sub-aperture signals are summed using the OS-CDM concept, illustrated in Fig. 2.

3. Power and Cost Reduction

As indicated in Table 1, if the sub-aperture in Fig. 2 is chosen to have 5×5 array elements, and ADCs are used to combine 8 sub-apertures, the total cost and power will be reduced by ~87% and ~90%, respectively. Alternatively, if the sub-apertures are 10×10 elements, the resulting savings could be as large as ~97%. That is, the proposed hybrid frequency independent/OS-CDM concept in Fig. 2 is highly promising for large reductions in size, cost, and power.

4. Conclusion

We presented a low-cost hardware reduced hybrid beamformer architecture for future 5G communications. The hybrid beamformer consists of a UWB aperture, a frequency independent self-mixing technique, and an OS-CDM concept. We showed that for very large arrays, using the hybrid frequency independent technique in conjunction with the OS-CDM concept promises greater than 95% reduction in cost and power as compared to conventional digital beamformers.

Acknowledgments

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John L. Volakis (S'77–M'82–SM'89–F'96) was born on May 13, 1956 in Chios, Greece and immigrated to the U.S.A. in 1973. He received the B.E. degree (summa cum laude) from Youngstown State University, Youngstown, OH, in 1978, and the M.Sc. and Ph.D. degrees from the Ohio State University, Columbus, in 1979 and 1982, respectively. He started his career at Rockwell International (1982–1984), now Boeing Phantom Works. In 1984, he was appointed Assistant Professor at the University of Michigan, Ann Arbor, becoming a full Professor in 1994. He also served as the Director of the Radiation Laboratory from 1998 to 2000. From January 2003 to July 2017, he served as the Roy and Lois Chope Chair Professor of Engineering at the Ohio State University, Columbus, and also as the Director of the ElectroScience Laboratory. Since July 2017, he is serving as the Dean of Engineering at the Florida International University. His primary research deals with antennas, computational methods, electromagnetic compatibility and interference, propagation, design optimization, RF materials, multi-physics engineering and bioelectromagnetics. He has published over 280 articles in major refereed journals, nearly 500 conference papers and 20 book chapters. He coauthored the following six books: Approximate Boundary Conditions in Electromagnetics (Institution of Electrical Engineers, London, 1995), Finite ElementMethod for Electromagnetics (IEEE Press, New York, 1998), Frequency Domain Hybrid Finite Element Methods in Electromagnetics (Morgan & Claypool, 2006), Computational Methods for High Frequency Electromagnetic Interference (Verlag, 2009), Small Antennas (McGraw-Hill, 2010), and edited the Antenna Engineering Handbook (McGraw-Hill, 2007). He has also written several well-edited coursepacks on introductory and advanced numerical methods for electromagnetics, and has delivered short courses on antennas, numerical methods, and frequency selective surfaces. Dr. Volakis was elected Fellow of the IEEE in 1996, and is a member of the URSI Commissions B and E. In 1998 he received the University of Michigan (UM) College of Engineering Research Excellence award, in 2001 he received the UM, Dept. of Electrical Engineering and Computer Science Service Excellence Award, and in 2010 he received the Ohio State Univ. Clara and Peter Scott award for outstanding academic achievement. He is listed by ISI among the top 250 most referenced authors. He graduated/mentored nearly 85 Ph.D. students/post-docs, and coauthored with them 14 best paper awards at conferences. He was the 2004 President of the IEEE Antennas and Propagation Society and served on the AdCom of the IEEE Antennas and Propagation Society from 1995 to 1998. He also served as an Associate Editor for the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION from 1988–1992, Radio Science from 1994–1997, and for the IEEE Antennas and Propagation Society Magazine (1992–2006), the J. Electromagnetic Waves and Applications and the URSI Bulletin. He chaired the 1993 IEEE Antennas and Propagation Society Symposium and Radio Science Meeting in Ann Arbor, MI., and co-chaired the same Symposium in 2003 at Columbus, OH.

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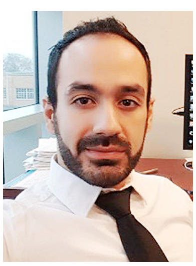

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