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IEICE Communications Express, Vol.1, 1–6

Model-Based Software Design of a Large-Scale Butler Matrix Beamformer for Hybrid 5G Subsystems

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Abstract: With 4G networks reaching their practical limits due to the ever-increasing demand for seamless connectivity, it has been clear that 5G is the future of communications. Millimetre-waves (mmWaves) is considered as a way forward with momentous research being carried out to provide cost-effective and easy-to-implement solutions, which can increase the data rate, provide low latency, and reliable radio connection. Inspired by this, a Butler matrix (BM) structure was considered in this work, due to its potential role in implementing large-scale beamforming networks (BFNs) for 5G systems. This would facilitate their deployment in both practical and analytical hybrid beamforming scenarios. Thus, a system-level model of large-scale BMs was realised in software to demonstrate its integrated structures and outputs. The proposed model can be significantly instrumental in the design of large-scale and hybrid wireless infrastructures at both sub-6 GHz and mmWave bands.

Keywords: BFN, Butler matrix, hybrid modelling, large-scale subsystem

Classification: Wireless communication technologies

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DOI: 10.1587/comex.2022XBL0026
Received February 16, 2022
Accepted April 04, 2022
Publicized April 12, 2022

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1 Introduction

According to the new Cisco Annual Internet Report that provides a global forecast of digital transformation across various business segments, there will be 5.3 billion total Internet users (66% of the global population) by 2023 [1]. This increase in traffic is in part due to the ever-increasing use of ‘data-hungry devices’, including mobile phones, laptops, and other smart devices. Considering this growing demand for high-quality mobile or multimedia applications, a paradigm shift through 5G is envisaged as the way forward, to effectively realise future communications [1, 2]. Moreover, due to the scarcity of frequencies available for mobile/wireless systems, mmWave bands were proved to be a viable substitute, especially within the 20 to 90 GHz range, to increase channel bandwidth, thus, resulting in higher throughput and data rates. The utilisation of these mmWaves as a possible solution has been predicted to achieve a tremendous capacity increase in comparison to current LTE networks [2]. However, using mmWaves proved to be more complex compared to currently deployed frequency bands, due to higher propagation losses, i.e., is a key factor in determining insertion loss (IL) of a device; with IL being defined as loss measured between a given source and receiver in dB. From this initial analysis, it quickly became clear that using these bands with current infrastructure could not provide needed low latency and high enough data rates. Consequently, the existing communication infrastructure was deemed not suitable and required to be updated [3]. As a result of reduced wavelengths at mmWave frequencies, antenna systems can have smaller physical dimensions compared to radio devices and subsystems used at current standards. This allows for beamforming (i.e., the concentration of power in a thin beam in a certain direction to increase signal power and to suppress interference) to be utilised as a possible solution to mitigate higher path loss and absorption at higher frequency bands. At these frequencies, systems can harbour a larger number of radiating elements, thus allowing beamforming arrays to play a vital part in the practical implementation of 5G. This would also provide a higher directive gain that improves signal-to-interference ratio (SIR), thus, increasing the capacity of the network. Also, levels of interference are reduced in the propagation environment, due to the provision of narrow beams, and the increasing possibility of sustaining adequate power in rural areas at the receiver terminal [3]. Therefore, to ensure optimal system-level design using numerical and simulation techniques, mainly in terms of implementation complexity, component count, and other figures of merit, the proposed large-scale BM was thoroughly developed. This structure can be significantly advantageous to the area of hybrid wireless design. It can be incorporated into core transceiver architectures and construct a suitable platform for the accurate assessment of real-world scenarios based on wireless beamforming. The proposed software-based model can reproduce integrated BFN front-ends, and exhibit output characteristics for system modelling and performance evaluation.

2 Array Beamforming Techniques

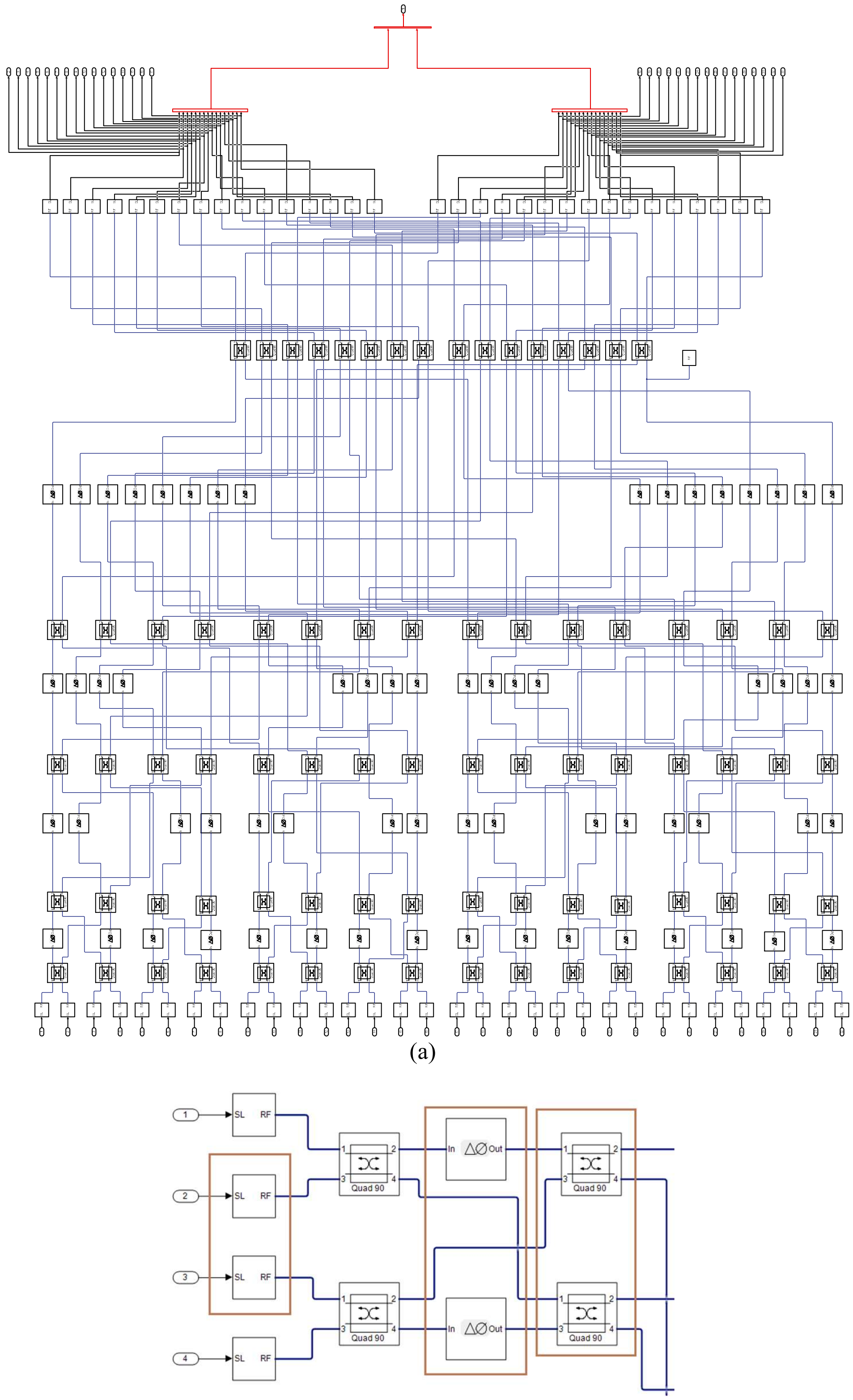
Amplitude and phase are two primary variables used for beamforming processing, being able to be applied in both analogue and digital baseband frameworks. Their crucial properties can be simultaneously utilised in hybrid beamforming, in which a switched-beam microwave-digital system enables the beam to adapt and alter per channel and propagation conditions [4]. Hence, generated patterns through BFNs can be adaptively interchanged from one beam to another, depending on the user's location, to efficiently realise cost-effective solutions for 5G systems. Thus, due to excessive cost and complex deployment of digital infrastructures at sub-6 GHz and mmWaves, core system design based on BFN was considered, to not only propose a new standalone theoretical BM-BFN structure, but to substantially facilitate the potential realisation of large-scale and hybrid multibeam front-ends [5]. Within analogue beamforming techniques, there are mainly two network types, lens-based devices and circuit-based systems [6]. This work was conducted based on the latter, in which networks are made by using various interconnected circuit components, including transmission lines (TLs), hybrid couplers; such as branch-line couplers (BLCs); splitters, and phase shifters (PSs); i.e., to provide a predefined phase shift to signal. Lengths of TLs are used to obtain phase shifts required to generate beam steering, while splitter ratios are used to regulate constant amplitude distributions [5, 6]. Also, BM has been established as one of the most commonly used BFNs in modern wireless communications [5]. A conventional BM typically is a symmetric $N \times N$ network, with N being a power of two in most implementations. This matrix is made up of TL, BLC, and PS components, with N input (i.e., beam) and N output (i.e., array) ports. A BLC can produce two signals that are 90° out of phase at array outputs with the same amplitude. The signal can be equally divided with varying phases into N outputs, by exciting each input beam port one by one, to dynamically perform beam scanning [4–6]. Also, BM, as the feeding of an array, generates N orthogonally spaced beams and provides desired input voltage standing wave ratio (VSWR) and beam port isolation, to ensure high-performance operation required for next-generation communications. Moreover, there has been considerable works reported on hardware aspects of microwave BM-BFNs, which has been thoroughly reviewed in [5]. However, there have been a few works focusing on the analytical and system-level aspects of BMs. Thus, inspired by seminal papers given in [7, 8], this work reports on the first software-based development of a 32-element BM.

3 Design and Modelling of a Large-Scale 32 × 32 BM-BFN

The proposed 32-element BM structure was systematically modelled in MATLAB and Simulink, based on conventional BM equations (i.e., not provided for sake of brevity). This module was comprised of three subsystems, including switch, BFN, and post-processing units, with the latter containing magnitude, phase, and array factor (AF) elements. Fig. 1 presents a developed BM model, thoroughly depicting its internal network of constituent system components and interconnections across the central BFN subsystem unit in the proposed hybrid communication framework. The post-processing unit transformed complex signals generated by this BFN unit into their corresponding magnitude and angle values. These resultant phase values (i.e., converted to degrees) were then passed to the AF submodule where they were stored and sent to MATLAB, to generate output characteristics of the large-scale model, in terms of normalised narrow-beam patterns; depicted in Fig. 2. These AF plots also aided to validate the correct operation of BM structures according to key figures of merit and to validate the performance of the software-based BM design. Besides, the overall purpose of the switch unit was to send a random signal to each of the beam ports in the BFN unit, one by one, to fully excite each port individually; hence, generating required phase differences. When implementing this 32-element unit, it was important to calculate the number of constituent components needed in each N-by-N iteration. BLCs were also implemented in p rows and $N/2$ BLCs per row. It should be noted that the large-scale BM-BFN was originally scaled up from conventional 4-element BM and its associated equations applicable to upscaling of the designed network. As one of the key building blocks of this subsystem, BLCs were effectively utilised in conjunction with PSs according to calculated and given values in Fig. 1, to provide predefined phase shifts to signals across the front-end. Within switching units, several blocks were essential to the consistent operation of BM. The switches were designed to output discrete-time sequences (i.e., repeated over a set duration) and to control generated outputs being fed to the BFN as inputs.

4 Conclusion

Model-based software design and implementation of a large-scale BM-BFN was thoroughly conducted in this work. This subsystem was able to effectively control phase and amplitude at each element of the array front-end and to generate narrow-beam patterns, to fully realise electronic beam steering for 5G hybrid beamforming applications. This investigation was the first of its kind in terms of software-based development of a large-scale BM-BFN, and as interdisciplinary research, it was conducted based on different elements from the broad areas of software systems, microwave technology, and 5G communications. Outputs based on the key figures of merit (i.e., circuit layout and patterns) were provided, to validate the operation and deployability of the model. This is of crucial importance for initial evaluations of this complex structure before its physical implementation. Lastly, a zoomable vector figure, given below, will enable its reproducibility and will enable its design enhancements by providing all circuit, connection, and component details, which can also be realised in other software environments (e.g., full-wave EM simulators).


(a)

(b)

Fig. 1. Zoomable model-based MATLAB/Simulink design of the proposed large-scale BM-BFN for hybrid 5G multibeam communication subsystems: (a) complete implementation of the 32 × 32 BFN with $p = 5$, BLCs = 80, and PSs = 64; (b) a segment of the developed structure in (a), comprising its constituent components and interconnections; i.e., ports, BLCs, and PSs, to facilitate its software reproducibility.

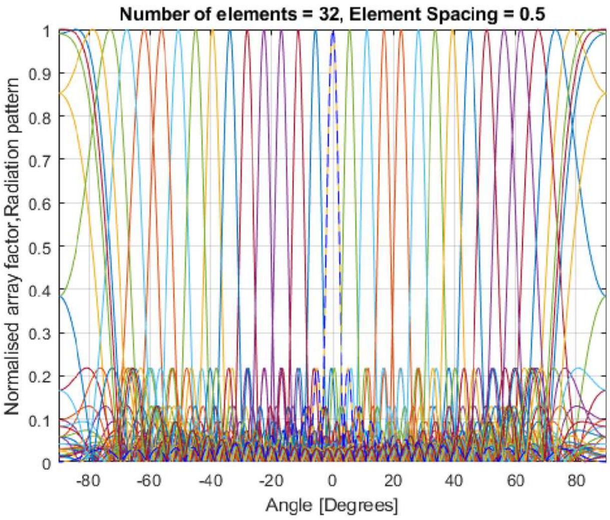


Fig. 2. Output characteristics of the proposed 32 × 32 BM-BFN, in terms of normalised AF plots (i.e., the main figure of merit) for 5G electronic beam steering applications.