The Magic of Quantum Computing for Microwave Computer-Aided Design: A Brief Overview

The Magic of Quantum Computing for Microwave Computer-Aided Design: A Brief Overview

Lida Kouhalvandi[1], Serdar Ozoguz[2], Ladislau Matekovits[3]
[1]*Department of Electrical and Electronics Engineering, Dogus University, Istanbul 34775, Turkey*
[2]*Department of Electronics and Communication Engineering, Istanbul Technical University, Istanbul, Turkey*
[3]*Department of Electronics and Telecommunications, Politecnico di Torino, Turin, Italy*

lida.kouhalvandi@ieee.org[1], ozoguz@itu.edu.tr[2], ladislau.matekovits@polito.it[3]

***Abstract*—Quantum computing has recently become an effective technology for tackling the drawbacks of microwave links where these were previously almost impossible. In that context, the quantum technology has made it possible not only to design a compact size system with improved performance but also to reduce the computational power and time. This presentation aims to provide a short overview through cases studies of the recent use of quantum computing in the design of the elements employed in the receiving section of a transceiver, such as active low-noise amplifier and passive phased-array antenna. This paper encourages the future studies in the domain of quantization effect of electromagnetic energy opening the way for other applications such as quantum communications and/or quantum radar schemes.**

***Index Terms*—Quantum computing, low-noise amplifier (LNA), phased-array antenna.**

I. Introduction

In satellite-to-earth communications, several challenges have usually been encountered in terms of data traffic, quality, and reliability. While engineers have been attempting to find relevant effective solutions, Quantum Computing (QC) has become more and more popular [1], [2]. QC, as the combination of the physics and computer science, together with modern microwave engineering have been found an attractive solution for the development of radar and related technologies [3].

Among others, BT has recently considered the hyper-sensitive quantum antenna technology, where it could improve the overall performance of fifth-generation (5G) networks [4]. Based on that technology, not only weaker signals could be even detected, but also the consumed energy of mobile network could be effectively reduced. Very recently, Infinion has studied Quantum computers that can improve the computational power [5]. Honeywell, one of the pioneers in the quantum computing domain, has focused on this technology leading to enhance efficiency and bandwidth of telecommunication systems [6]. Thales has also running projects on the quantum antenna, where they recently reported a significant size reduction of a wireless device being comparable to the finger tip [7] while enhancing the security and defense aspects of design.

In transceiver communication systems, the most important blocks are the antenna and the amplifiers. Designing high performance active and passive devices plays important roles in such systems [3]. Recently, QC has proved its beneficial aspects in the design of the microwave link [3]. Therefore, the main goal here is to shed light on the recent advances in that domain by providing a very short overview of the relevant case studies conducted on the design of the elements used in the communication systems such as the low-noise amplifier (LNA) and phased-array antenna.

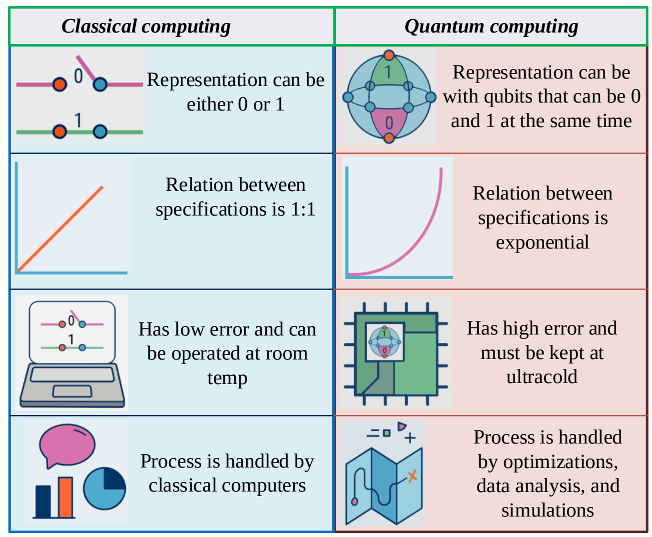

Fig. 1. Theoretical differences between classical computing (left) and quantum computing (right) [8].

This paper is organized as follows: Section II provides the general overview on QC. Section III and Sec. IV address the application of QC in the design of an amplifier and an array antenna, respectively. Section V concludes the paper and points out the future challenges.

II. Quantum computing in a nutshell

QC, as an emerging technology to solve complex problems in microwave technologies and devices, can in fact provide the platform for optimizing various design parameters in the targeted specifications. Compared to classical computing methods, QC has several theoretical differences as outlined in Fig. 1 [8].

Practically, the performance of QC depends on the superposition by having qubits around [9]. While Fig. 1 describes the

Classical computing	*Quantum computing*
Employed for multipurpose devices	High-speed computers are used
Stored data is in bits	The stored data is in quantum bits
Behaves as deterministic (can results in the same output for the same input data)	Behaves as probabilistic (can results in multiple outputs for the same inputs)
Data processing is in sequentianol	Data processing is in parallel
Boolean algebra can be used	Linear algebra can be used
Classical physics is employed	Quantum machanics is employed

Fig. 2. Classical versus quantum computing methods in terms of data type and application .

differences between QC and classical computing approaches, where the calculations are performed around 0 and 1 orbits, Fig. 2 explains the use of QC depending on the type of data and application.

III. Application of Quantum Computing in Amplifier Designs

In the world of electronics, designing virtual amplifiers is required to be used in the applications as diverse as in satellite communications, military, quantum computing, and fifth generation (5G) wireless. Quantum amplifiers are linear quantum systems of which functioning is described by linear quantum theory. The design of such amplifiers can be based on quantum optic technology or microwave technology [10]. This section highlights the critical aspects in designing amplifiers using QC.

A. Case Study Project: QC in Amplifier Designs

Cryogenic amplifiers, currently examined in satellite-to-earth stations, are operating below $-180°$C and are typically used in quantum computers. Those amplifiers are a subset of microwave LNAs with low power dissipation [11]. For instance, they are employed in ultra-sensitive quantum receiver, where the quality of amplified signal is important. Moreover, they are capable of supporting sub-atomic environment. In the LNA designs, the noise figure (NF) is considered the most important specification. It is expressed as (1):

$$\mathrm{NF} = 10 \times \log\left(F_{min} + \frac{4\mathrm{R_n}\left|(\Gamma_s - \Gamma_{opt})^2\right|}{\left|(1-\Gamma_s)^2\right|\left|(1+\Gamma_{opt})^2\right|}\right) \qquad (1)$$

where F_{min} represents the minimum noise of bias circuit, R_n is the total noise impedance of circuit, Γ_s and Γ_{opt} refer to the source reflection coefficient and optimum noise source reflection coefficients, respectively.

Such amplifiers can be as small enough as monolithic microwave integrated circuits (MMICs) including GaAs metamorphic InP high electron mobility transistors (mHEMTs). To assess the overall performance of active devices such as LNA, NF, power consumption and gain as well as intermodulation

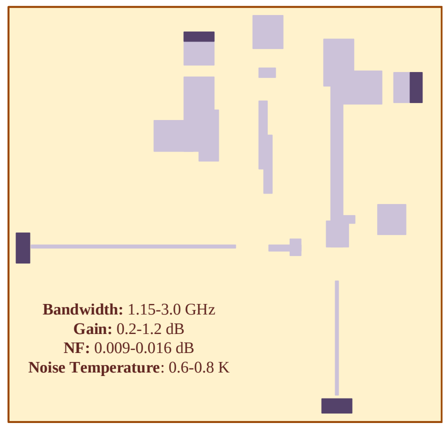

Fig. 3. Layout of the designed LNA in operating in the 1.15−3 GHz frequency range.

distortion (IMD) and signal-to-noise ratio (SNR) specifications are the most important parameters to be considered. In [12], the LNA designed for quantum applications provides up to 1.2 dB gain in the 1.15−3 GHz frequency range; the layout is depicted in Fig. 3. Figure 4 shows the simulated NF results of the designed LNA in [12] as a function of frequency for different input power levels ranging from −35 dBm to −120 dBm. As it can be seen in the enlarged-section within Fig. 4, the obtained total NF in the considered frequency range is very low (i.e. 0.01 dB) for an input power of −50 dBm, which is very suitable for the quantum applications. That was in fact obtained through carefully optimizing the matching networks of the LNA together with applying techniques such as negative feedback and degenerative impedance. Further noise analysis such as SNR, gain, and IMDs is also provided in that study, which is not discussed here for the sake of brevity.

To sum up, the authors of the study in [12] have demonstrated the feasibility to apply the quantum theory in the design of an active element used in any communication systems achieving rapidly the desired NF specification for their proposed LNA with a much decreased total power consumption as a promising candidate for quantum applications.

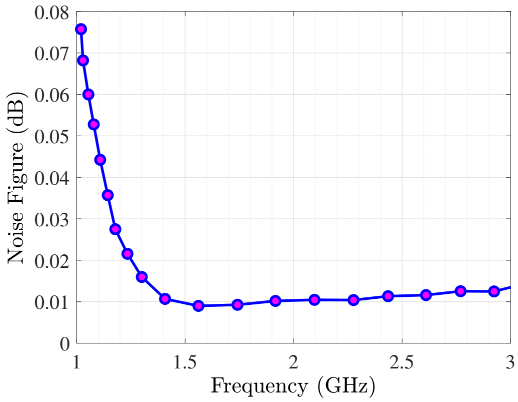

Fig. 4. NF specification of the LNA in [12].

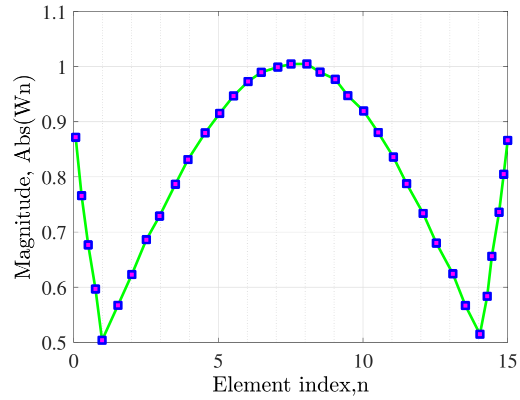

Fig. 5.

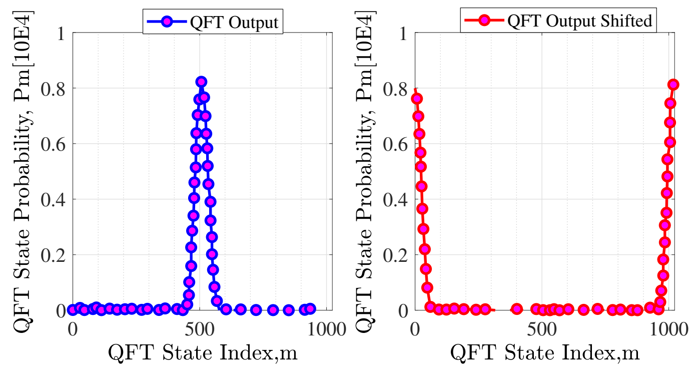

Fig. 6.

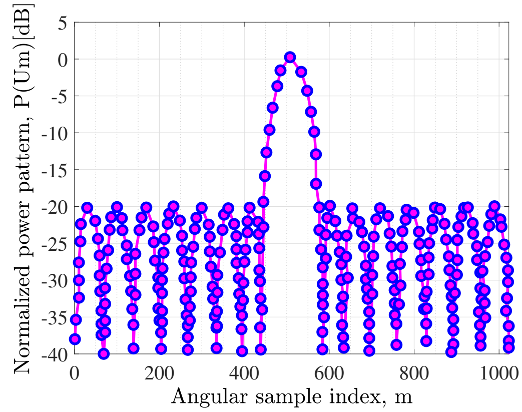

Fig. 7.

Fig. 8. Power radiation pattern (N=16, SLL=-20 dB) [16]: (a) the elements excitation for the Dolph-Chebychev pattern, (b) the probability of the QFT output states, and (c) the power pattern computed by the DFT/QFT methods when considering the main-lobe beam directed along the broadside direction θ=0°.

IV. APPLICATION OF QUANTUM COMPUTING IN ANTENNA TECHNOLOGY

With the aim not only to miniaturize the radio frequency equipment but also to reduce the portable energy consumption, quantum antenna technology can be considered an inspiring potential solution. The rapid pace of developing such a technology has additionally brought projects to the market investing on the improvement of the operational sensitivity of receivers as well as the optimal generation and detection of analogue and digital modulation [13].

Unlike the classical antenna design, where the electrical size is rather large to efficiently capture the electromagnetic (EM) field, the quantum antenna (QA) occupies a much smaller area. Depending on the quantum effect, the QA can be responsive to EM fields. Using the electromagnetically induced transparency, the QA will be sensitive to electric field component of the EM waves, whereas using the Josephson effect, the QA will be sensitive to the magnetic fields.

A. Case Study Project: QC in Radiation Pattern Power Analysis of an Array Antenna

Phased array antennas are indispensable candidates for various radio frequency applications as diverse as autonomous driving, biomedical image processing, and more, due to their highly reconfigurable capabilities thanks to the amplitudes and phases excitation of the individual elements of the array [14].

With the exponential pace of computer-based technologies evolved from the quantum theory principles, there has been increasing attention towards the analysis of array antennas through QC [15]. In the framework of QC, a recent study in [16] reports a new method to investigate the power pattern generated from a uniformly-spaced linear phased array antenna. It is based on the quantum Fourier transform (QFT) algorithm, where a preliminary proof-of-concept result has been analyzed to point out the advantages of the proposed method [16].

To that aim, a linear phased array composed of N equi-spaced ideal and isotropic elements and having complex excitation equal to $w = \{w_n\colon n = 0, \ldots, N-1\}$ is considered. Its radiation pattern can be derived by the array factor function $A(u)$ mathematically expressed as [16]:

$$A(u) = \sum_{n=0}^{N-1} w_n e^{jkndu} \tag{2}$$

where $u = \cos\theta$ is the cosine angular direction, $k = 2\pi/\lambda$ is the wave number, λ being the wavelength, and d is the inter-element distance. An excitation vector of 1024 entries (N=1024) was considered, in which only the first 16 elements were set following a Dolph-Chebychev distribution in order to obtain a power pattern with a beam directed towards the broadside direction (i.e., θ=0°) and a -20 dB side-lobe level (SLL), as can be seen in Fig. 5.

In order to apply the QFT algorithm to compute the power pattern of the array antenna from the excitations vector w, the input state vector $|w\rangle$ was defined as follows [16]:

$$|w\rangle = \sum_{n=1}^{N} \widehat{w}_n |b_n\rangle \tag{3}$$

where $\widehat{w}_n = w_n / \|w\|, n = 1, \ldots, N, \|.\|$ being the norm operator, and $|b_n\rangle = |q_L^{(n)}, ..., q_1^{(n)}\rangle$ is a multi-qubit state originated from the concatenation of L=$\log_2(N)$ single-qubits, corresponding to the binary representation of the index n.

In [16], a L=10 qubit register was initialized as in the above equation and the QFT was applied in that study. The QFT operation was then repeated 105 times to statistically validate that proposed approach, achieving the set of N probabilities shown in Fig. 6. Finally, to calculate the power pattern, the state probabilities were ordered from $|N\text{-}1\rangle$ up to $|0\rangle$ and a $N/2 = 512$ positions circular shift was applied (Fig. 6). Fig 7 demonstrates the perfect agreement between the power pattern obtained by using the standard DFT technique and that proposed QFT approach in [16]. However, compared to the classical DFT whose complexity scales as $N \log N$, the QFT led to a significantly reduced computational time due to $(\log N)^2$ scaling, provided by the quantum superposition and parallelism. A further analysis to validate the effectiveness of that method with complex excitations (applying a phase front to the Dolph-Chebychev distribution with the aim to change the pointing direction of the main beam to θ=45°) was also carried out in that study [16].

To sum up, the authors of the study in [16] have demonstrated that not only the peculiarities of the QFT but also the proportionality of the probabilities observed for the output state vector to the squares of the state coefficients, resulted in obtaining the power pattern of the array in a straightforward manner with a huge reduction of the computational load as compared to classical computation methods.

V. Conclusion and Perspectives

Quantum computing has become the emerging technology to solve complex problems much more easier and faster compared to the classical computers with traditional solutions. Since many companies have lately focused on this technology to design high-performance circuits, the present communication describes two recently published relevant case studies of the use of QC in the design of a LNA and a phased array antenna.

In the first case study, it was demonstrated that QC led to a rapid design with much decreased total power consumption of an active LNA circuit. As far as passive circuits is concerned, QC was shown in the second considered case to make it possible to obtain the power pattern of an array antenna in a very straightforward manner with a huge reduction in computational power and time as compared to classical computation methods.

Since machine learning has found early success in speeding up and accurately designing high frequency component designs, future perspective would involve exploring the interaction between quantum computing and machine learning approaches to find out whether quantum computers can further reduce the time it would take to train or evaluate developed machine learning models for the elements used in microwave communication links. Unlike the conventional approaches, with the help of intelligent-based methods, the concept of electromagnetic radiation can be improved to be further employed in quantum communications.

References

[1] B. Aja, K. Schuster, F. Schafer, J. D. Gallego, S. Chartier, M. Seelmann-Eggebert, I. Kallfass, A. Leuther, H. Massler, M. Schlechtweg, C. Diez, I. Lopez-Fernandez, S. Lenz, and S. Turk, "Cryogenic low-noise mHEMT-based MMIC amplifiers for 4–12 ghz band," *IEEE Microwave and Wireless Components Letters*, vol. 21, no. 11, pp. 613–615, 2011.

[2] Y. Guo and R. Ziolkowski, *Antenna and Array Technologies for Future Wireless Ecosystems*. Wiley-IEEE Press, 2022.

[3] J. C. Bardin, D. H. Slichter, and D. J. Reilly, "Microwaves in quantum computing," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 403–427, 2021.

[4] "BT trials new hyper-sensitive quantum antenna technology," http://thefastmode.com/, accessed: 2022-08-11.

[5] "Infineon participates in 6 research projects, expands commitment to quantum computing," http://thequantuminsider.com/, accessed: 2022-08-11.

[6] "Honeywell quantum solutions," http://honeywell.com/us/en/company/quantum, accessed: 2022-08-11.

[7] "Quantum antenna by thales," http://thales.com, accessed: 2022-08-11.

[8] "Quantum computing vs. classical computing in one graphic," http://cbinsights.com/research/quantum-computing-classical-computing-comparison-infographic/, accessed: 2022-04-11.

[9] "What is quantum computing?" http://www.iberdrola.com/innovation/what-is-quantum-computing, accessed: 2022-04-11.

[10] I. R. Petersen, "Using systems and control theory ideas in the design of quantum amplifiers," in *2021 IEEE Conference on Control Technology and Applications (CCTA)*, 2021, pp. 523–523.

[11] X. Niu, L. Li, X. Wu, and D. Wang, "A wideband cryogenic readout amplifier with temperature-insensitive gain for snspd," *Sensors*, vol. 22, no. 3, 2022. [Online]. Available: https://www.mdpi.com/1424-8220/22/3/1225

[12] A. Salmanogli, "Design of ultra-low noise amplifier for quantum applications (qlna)," 2021. [Online]. Available: https://arxiv.org/abs/2111.15358

[13] "Howard Watson, Chief Technology Officer of BT, BT trials new hyper-sensitive quantum antenna technology," http://thefastmode.com/technology-solutions/24946-bt-trials-new-hyper-sensitive-quantum-antenna-technology:, accessed: 2022-04-11.

[14] P. Rocca, G. Oliveri, R. J. Mailloux, and A. Massa, "Unconventional phased array architectures and design methodologies—a review," *Proceedings of the IEEE*, vol. 104, no. 3, pp. 544–560, 2016.

[15] P. Rocca, N. Anselmi, G. Oliveri, A. Polo, and A. Massa, "Antenna array thinning through quantum fourier transform," *IEEE Access*, vol. 9, pp. 124 313–124 323, 2021.

[16] L. Tosi, N. Anselmi, A. Polo, and P. Rocca, "Array antenna power pattern analysis through quantum computing," in *2022 16th European Conference on Antennas and Propagation (EuCAP)*, 2022, pp. 1–3.