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Design Methods for Butler Matrices at Millimetre-Wave Frequencies

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Eligia Simionato

Design Methods for Butler Matrices at Millimetre-Wave Frequencies

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POTENTIAL IMPACT OF THIS RESEARCH

The primary potential impact of this research is scientific, due to the development of novel devices that operate at extremely high frequencies, possibly contributing to advancements in future generations of mobile communications, aligning with Sustainable Development Goal 9: Industry, Innovation, and Infrastructure.

IMPACTO POTENCIAL DESTA PESQUISA

O principal impacto potencial desta pesquisa é científico, devido ao desenvolvimento de novos dispositivos que operam em frequências extremamente altas, possivelmente contribuindo para avanços nas futuras gerações de comunicações móveis, alinhando-se ao Objetivo de Desenvolvimento Sustentável 9: Indústria, Inovação e Infraestrutura.

IMPACT POTENTIEL DE CETTE RECHERCHE

L'impact potentiel principal de cette recherche est scientifique, en raison du développement de nouveaux dispositifs fonctionnant à des fréquences extrêmement élevées, pouvant contribuer aux avancées des futures générations de communications mobiles, s'alignant ainsi sur l'Objectif de Développement Durable 9 : Industrie, Innovation et Infrastructure.



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To the memory of Edevino Simionato

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If it weren't for the fact that I needed a serious title (because this is a serious dissertation), I would've titled it "How to Tell Radiation Beams Where to Go Without Yelling at Them", or even "The Art and Occasional Science of Convincing Invisible Waves to Go Exactly Where You Want Them, Even If They Have Other Ideas". Oh well.
(The author)

ABSTRACT

Beamforming networks have been a key enabling technology for applications operating at millimetre-wave frequencies, as they provide adaptive, highly directive beams that mitigate the effects of increased attenuation at extremely high frequencies. As research efforts shift to enabling operation at the higher end of the millimetre-wave range to support emerging spectrum-reliant wireless communication applications, extensive use of beamforming is one of the strategies that will allow for mobility and improved channel propagation characteristics. In this context, this dissertation aims to explore different design methods for the Butler matrix, a well-known beamforming network, at the D-band (110 GHz to 170 GHz), one of the frequency ranges considered in the early initiatives to adapt to higher frequencies. In addition, this work focuses on design methods that enable miniaturisation, motivated by the requirements of reduced cost and compactness driven by consumer market demands. The research consisted of the study of foundational concepts involved in the design and analysis of a Butler matrix through simulations and measurements of an exploratory design; the simulation-based design of a Butler matrix miniaturised using the slow-wave technique and considering the Metallic-nanowire-Membrane technology; and the design, electromagnetic analysis, and measurements of transdirectional couplers, which were subsequently used in a preliminary circuit design of a Butler matrix considering the BiCMOS technology. The following characteristics are desired for the Butler matrix: wideband operation, balanced amplitudes at the output ports, and phase differences between outputs with minimal deviation from ideal values. Using the exploratory design as a reference, the designed slow-wave Butler matrix operates within a similar bandwidth but exhibits significantly higher amplitude imbalance and greater deviation from the ideal phase differences. In contrast, the Butler matrix with transdirectional couplers operates within a substantially larger bandwidth than the exploratory design, with only a slightly higher amplitude imbalance but greater deviation from the ideal phase differences. Nevertheless, the slow-wave design and the transdirectional-coupler-based design achieved, respectively, a 92.8% and a 99.4% reduction in the occupied area compared to the exploratory design.

KEYWORDS: Beamforming Networks. BiCMOS. Butler Matrix. Metallic-nanowire-Membrane. Slow Wave. Transdirectional Couplers.

RESUMO

As redes de formação de feixes (*beamforming*) têm sido uma das principais tecnologias habilitadoras para aplicações que operam em frequências de ondas milimétricas, uma vez que fornecem feixes adaptativos e altamente diretivos que mitigam os efeitos da atenuação elevada em frequências extremamente altas. À medida que os esforços de pesquisa se voltam para viabilizar a operação no extremo superior da faixa de ondas milimétricas, com o objetivo de prover suporte à aplicações emergentes de comunicação sem fio dependentes de disponibilidade de espectro, o uso extensivo de técnicas de *beamforming* constitui uma das estratégias que permitirão mobilidade e melhorias nas características de propagação do canal. Nesse contexto, esta dissertação tem como objetivo explorar diferentes métodos de projeto para a matriz de Butler, uma conhecida rede de *beamforming*, na banda D (110 GHz a 170 GHz), uma das faixas de frequência consideradas nas iniciativas iniciais de adaptação a frequências mais elevadas. Além disso, este trabalho concentra-se em métodos de projeto que possibilitem a miniaturização, motivado pela demanda de dispositivos compactos e de custo reduzido impulsionada pelo mercado consumidor. A pesquisa consistiu no estudo dos conceitos fundamentais envolvidos no projeto e na análise de uma matriz de Butler por meio de simulações e medições de um design exploratório; no projeto, baseado em simulações, de uma matriz de Butler miniaturizada utilizando a técnica de ondas lentas e considerando a tecnologia *Metallic-nanowire-Membrane*; e no projeto, análise eletromagnética e medições de acopladores transdirecionais, que posteriormente foram utilizados em um projeto circuital preliminar de uma matriz de Butler considerando a tecnologia BiCMOS. As seguintes características são desejadas para a matriz de Butler: operação em banda larga, amplitudes equilibradas nas portas de saída e diferenças de fase entre as saídas com desvio mínimo em relação aos valores ideais. Utilizando o design exploratório como referência, a matriz de Butler projetada com a técnica de ondas lentas opera dentro de uma largura de banda semelhante, porém apresenta um desequilíbrio de amplitude significativamente maior e um desvio mais acentuado em relação às diferenças de fase ideais. Em contrapartida, a matriz de Butler baseada em acopladores transdirecionais opera em uma largura de banda substancialmente maior do que a do design exploratório, com apenas um desequilíbrio de amplitude ligeiramente superior, mas com maior desvio em relação às diferenças de fase ideais. Ainda assim, o design baseado em ondas lentas e o design baseado em acopladores transdirecionais alcançaram, respectivamente, uma redução de 92,8% e 99,4% da área ocupada em comparação com o design exploratório.

PALAVRAS-CHAVE: Redes de Formação de Feixes. BiCMOS. Matriz de Butler. *Metallic-nanowire-Membrane*. Ondas Lentas. Acopladores Transdirecionais.

RÉSUMÉ

Les réseaux de formation de faisceaux (*beamforming*) constituent une technologie clé pour les applications fonctionnant aux fréquences millimétriques, car ils permettent de générer des faisceaux adaptatifs et hautement directifs capables d'atténuer les effets des pertes de propagation élevées à des fréquences extrêmement hautes. À mesure que les efforts de recherche se concentrent sur la mise en œuvre de systèmes opérant dans la partie supérieure du spectre des ondes millimétriques afin de répondre aux besoins des applications émergentes de communications sans fil dépendantes de la disponibilité du spectre, l'utilisation intensive du *beamforming* apparaît comme l'une des stratégies permettant d'assurer la mobilité ainsi que d'améliorer les caractéristiques de propagation du canal. Dans ce contexte, cette thèse a pour objectif d'explorer différentes méthodes de conception de la matrice de Butler, un réseau de formation de faisceaux largement reconnu, dans la bande D (110 GHz à 170 GHz), l'une des plages de fréquences envisagées dans les premières initiatives visant l'exploitation de fréquences plus élevées. En outre, ce travail se concentre sur des méthodes de conception permettant la miniaturisation, motivé par les exigences de coût réduit et de compacité imposées par le marché grand public. Les travaux de recherche ont consisté en l'étude des concepts fondamentaux impliqués dans la conception et l'analyse d'une matrice de Butler au moyen de simulations et de mesures réalisées sur une conception exploratoire ; en la conception par simulation d'une matrice de Butler miniaturisée à l'aide de la technique des ondes lentes et en considérant la technologie *Metallic-nanowire-Membrane* ; ainsi qu'en la conception, l'analyse électromagnétique et la caractérisation expérimentale de coupleurs transdirectionnels, lesquels ont ensuite été utilisés dans une conception circuitaire préliminaire d'une matrice de Butler sur la technologie BiCMOS. Les caractéristiques recherchées pour la matrice de Butler sont les suivantes : un fonctionnement large bande, des amplitudes équilibrées aux ports de sortie et des écarts de phase entre les sorties présentant une déviation minimale par rapport aux valeurs idéales. En prenant la conception exploratoire comme référence, la matrice de Butler miniaturisée par technique des ondes lentes fonctionne sur une bande passante similaire, mais présente un déséquilibre d'amplitude significativement plus important ainsi qu'une déviation plus marquée des écarts de phase idéaux. À l'inverse, la matrice de Butler basée sur des coupleurs transdirectionnels fonctionne sur une bande passante nottament plus large que celle de la conception exploratoire, avec un déséquilibre d'amplitude seulement légèrement supérieur, mais une déviation plus importante par rapport aux écarts de phase idéaux. Néanmoins, la conception basée sur la technique des ondes lentes et celle fondée sur les coupleurs transdirectionnels ont permis de réduire la surface occupée de 92,8% et 99,4%, respectivement, par rapport à la conception exploratoire.

MOTS CLÉS: Réseaux de Formation de Faisceaux. BiCMOS. Matrice de Butler. *Metallic-nanowire-Membrane*. Ondes Lentes. Coupleurs Transdirectionnels.

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LIST OF ABBREVIATIONS AND ACRONYMS

5G	Fifth-generation of mobile communications
6G	Sixth-generation of mobile communications
AAO	Anodic Alumina Oxide
AMS	Antenna Measurement System
AUT	Antenna Under Test
BiCMOS	Bipolar Complementary Metal-Oxide-Semiconductor
CAD	Computer-Aided Design
COD	Codirectional
CPW	Co-Planar Waveguide
CTD	Contradirectional
dB	Decibel
DC	Direct Current
DGS	Defective Ground Structure
DUT	Device Under Test
EB	Exabytes
FEM	Finite Element Method
FeMBB	Further enhanced Mobile BroadBand
GHz	Gigahertz (10^9 Hertz)
HFSS	High Frequency Structure Simulator
IoE	Internet of Everything
ITU	International Telecommunications Union
MBBL	Mobile BroadBand and Low Latency
mLLMT	massive Low-Latency Machine-Type communications
MnM	Metallic-nanowire-Membrane
MoM	Method of Moments

PCell	Parametrised Cell
QWT	Quarter Wave Transformer
RA	Reference Antenna
RF	Radio Frequency
SiO ₂	Silicon Dioxide
SLL	Side-Lobe Level
S-G	Savitzki-Golay
THz	Terahertz (10^{12} Hertz)
TRD	Transdirectional
TRL	Through-Reflect-Line
TSV	Through Substrate Via
umMTC	ultra-massive Machine-Type Communications

LIST OF SYMBOLS

ϵ_r	relative permittivity
$\tan \delta$	dielectric loss tangent
ψ	ideal progressive phase difference between the outputs of the Butler matrix
f	frequency
f_0	design frequency
$\Delta\phi$	phase difference between two adjacent output ports of the Butler matrix
S	scattering parameter
λ_g	guided wavelength
Θ	elevation angle
Φ	azimuth angle
v_ϕ	(single-mode) phase velocity
ω	angular frequency
ℓ	physical length
θ	(single-mode) electrical length
c	speed of light in a vacuum
$\epsilon_{r,\text{eff}}$	effective relative permittivity
L	(single-mode) inductance per unit length
C	(single-mode) capacitance per unit length
Z_0	(single-mode) characteristic impedance
β	(single-mode) phase constant
λ_0	free-space wavelength
$Z_0^{\{E,O\}}$	{even, odd}-mode characteristic impedance
$\theta^{\{E,O\}}$	{even, odd}-mode electrical length
ℓ_{TRD}	necessary physical length to achieve TRD operation
$\beta^{\{E,O\}}$	{even, odd}-mode phase constant

$L^{\{E,O\}}$	{even, odd}-mode inductance per unit length
$C^{\{E,O\}}$	{even, odd}-mode capacitance per unit length
k	coupling coefficient
$S^{\{E,O\}}$	{even, odd}-mode scattering parameter
$V^{\{C,D\}}$	{common, differential}-mode voltage
$I^{\{C,D\}}$	{common, differential}-mode current
$Z_0^{\{C,D\}}$	{common, differential}-mode characteristic impedance
$\gamma^{\{C,D\}}$	{common, differential}-mode propagation constant
$\gamma^{\{E,O\}}$	{even, odd}-mode propagation constant
$\alpha^{\{E,O\}}$	{even, odd}-mode attenuation constant
$\delta^{\{E,O\}}$	{even, odd}-mode propagation delay per unit length
$v_\phi^{\{E,O\}}$	{even, odd}-mode phase velocity
T	chain scattering parameter

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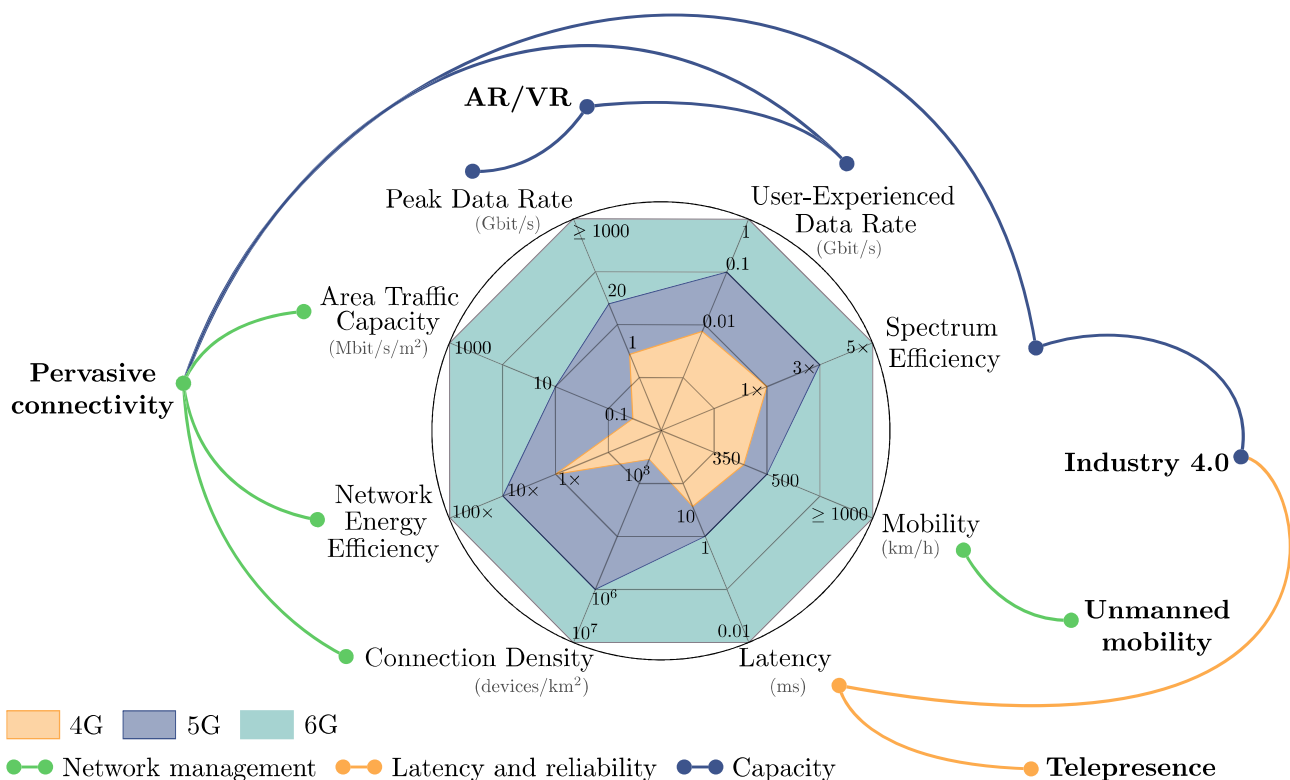
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1 INTRODUCTION

1.1 ADVANCEMENTS IN WIRELESS COMMUNICATION NETWORKS THROUGH THE USE OF MILLIMETRE WAVE FREQUENCIES

In the dynamic scenario of wireless communication networks, the shift from fifth-generation (5G) to the anticipated sixth-generation (6G) has become a significant focus. Initially, 5G networks were designed to provide high data rates with near-zero latency and utmost reliability to meet the needs of our data-reliant society (XING; RAPPAPORT, 2021; RAPPAPORT et al., 2019; PI; KHAN, 2011). However, the limitations of 5G networks become apparent when considering the possible requirements for emerging use cases, such as holographic telepresence, enhanced telemedicine, the Internet of Everything (IoE), and more (see Figure 1) (GIORDANI et al., 2020). Additionally, Ericsson (2025) projects that global data traffic, including mobile and fixed wireless access, will reach 232 Exabytes (EBs) per month by the end of this year (2026) and 425 EB/month by 2030. According to other estimations reported by the International Telecommunications Union (ITU), global mobile traffic is expected to grow at an annual rate of 55% between 2020 and 2030, reaching 938 EB/month by the end of 2026 and 5016 EB/month by 2030 (ITU, 2015a).

Figure 1 – 6G use cases and key performance indicators.



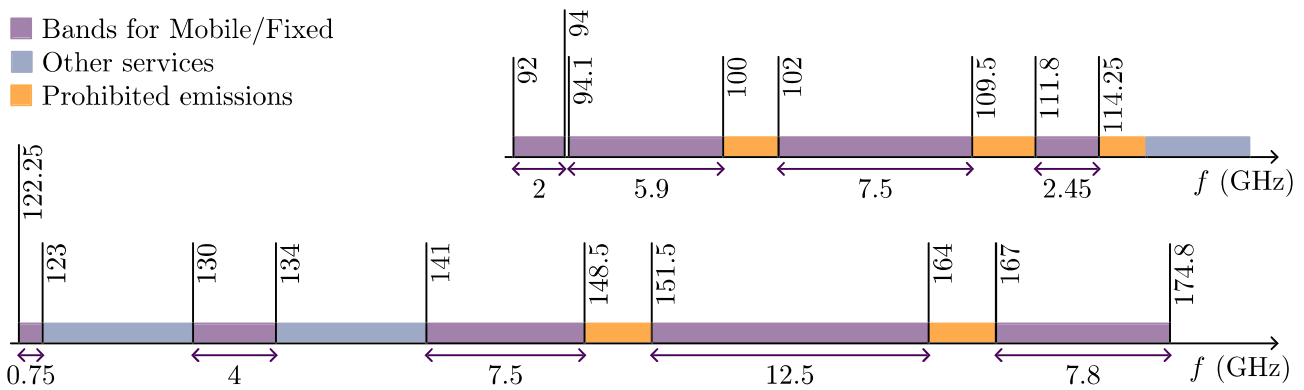
Source: Adapted from Giordani et al. (2020), Alwis et al. (2021) and ITU (2015b).

To address these demands, 5G introduced different configurations, each involving trade-offs on latency, energy consumption, costs, hardware complexity, throughput, and end-to-end reliability. In contrast, 6G will be developed to jointly meet rigorous network demands and requirements,

including Further enhanced Mobile Broadband (FeMBB), ultra-massive Machine-Type Communication (umMTC), Mobile BroadBand and Low Latency (MBLL), and massive Low-Latency Machine Type communication (mLLMT) (ALSABAH et al., 2021; GIORDANI et al., 2020; ALWIS et al., 2021).

To meet the aforementioned requirements, 6G networks are expected to rely on both conventional spectrum bands (such as sub-6GHz and the lower end of millimetre waves) and frequencies that have not been previously considered for cellular standards. One of these novel frequency bands is the terahertz (THz) band, spanning from 0.1 to 10 THz (JORNET; AKYILDIZ, 2011). Initiatives to adapt to these higher frequencies will commence in the sub-THz spectrum, which ranges from 100 GHz to 300 GHz and primarily includes the W and D bands (GIORDANI et al., 2020; ERICSSON, 2026b; ERICSSON, 2026a). Currently, numerous blocks of spectrum are in the process of being allocated, as depicted in Figure 2.

Figure 2 – Frequency allocations for the W and D bands.



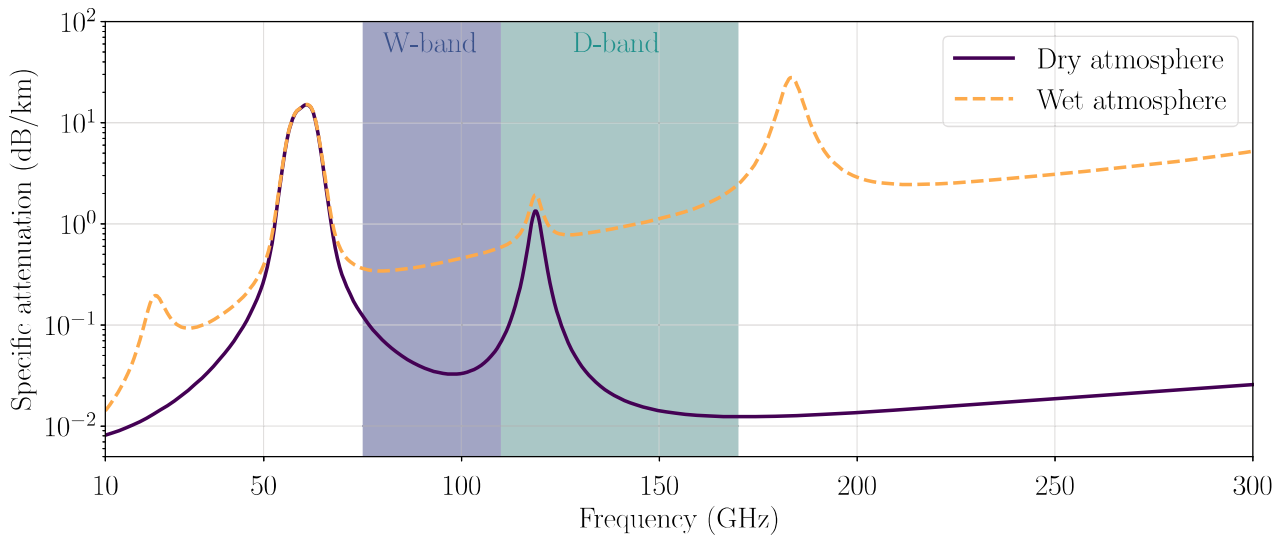
Source: Adapted from Ericsson (2026b).

Operating at higher frequencies presents immediate challenges primarily due to the attenuation caused by atmospheric gaseous, dust and rain (see Figure 3), as well as the intensified effects of free-space path loss, as a direct result of the Friis transmission law (ITU, 2022; MARCUS; PATTAN, 2005; WEI et al., 2014). Consequently, when it comes to outdoor communications over extensive distances, sub-THz frequencies might not be a feasible choice. However, these frequencies hold significant potential for indoor or close-range applications. These applications might include precise positioning and high-resolution sensing, as well as high-capacity wireless backhaul solutions, benefiting from improved physical layer confidentiality due to radio confinement and enhanced antenna directivity (BICAÏS et al., 2021; ETSI, 2018; ETSI, 2019).

Hence, extensive use of beamforming – adaptive, highly directive, electronically steerable beams – is one of the key enabling technologies that will allow for mobility and improve the channel propagation characteristics at sub-THz frequencies (ERICSSON, 2026b; DOAN et al., 2004; PI; KHAN, 2011).

Analog beamforming is a likely choice for implementation due to its cost-efficiency and lower power consumption (ERICSSON, 2026b). This approach utilizes a single RF chain shared among all antenna elements. Each antenna receives a phase-shifted version of the same transmit signal, with the phase shift determined based on the desired beamforming direction (WU et al., 2021; NSENGA; BOURDOUX; HORLIN, 2010; CHOUDHURY, 2015).

Figure 3 – Specific attenuation as a function of frequency for dry and wet atmosphere, with highlights for the W and D bands.



Source: Author, with data from ITU (2022), utilizing Python library provided by Portillo (2017).

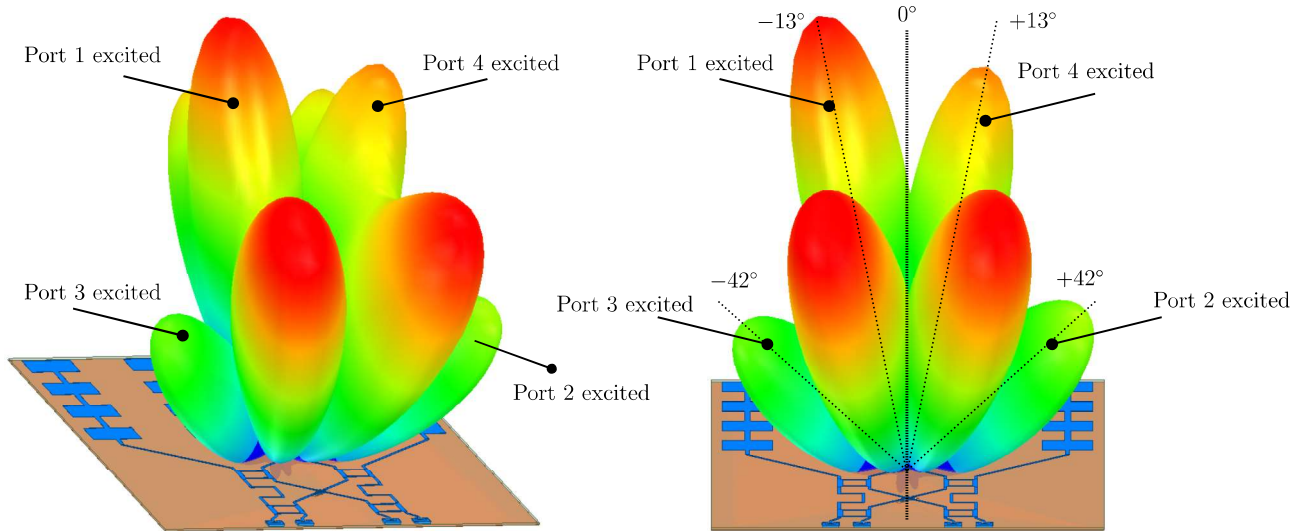
Known analog beamforming architectures can be described either as a phased array or as a switched-beam antenna. The phased array, while effective, is rather costly as complexity of systems grows with the number of elements that are required to ensure the appropriate angular resolution of the system. An alternative architecture is the switched-beam antenna array fed through a beamforming network, which aids in reducing system complexity while achieving the appropriate angular resolution (ACRI, 2020).

A well-known beamforming network solution is the Butler matrix, which is able to simultaneously provide excellent matching, isolation and equal power division. Furthermore, compared with other beamforming networks, the Butler matrix has some attractive features such as the realizable bandwidth and its structural simplicity (ACRI, 2020).

Butler Matrices are composed of directional couplers, crossovers, and fixed phase shifters. These primary components are interlaced in a way such that a signal introduced at one input produces approximately equal amplitude excitations at all outputs but with a constant phase difference between them, resulting in radiation at a certain angle in space, as illustrated in Figure 4. RF switches are utilized to control which port is excited, thus allowing to control the beam direction (MOODY, 1964; DELANEY, 1962).

The work presented in this dissertation is primarily motivated by two factors: first, the use of beamforming networks to enable the use of higher frequencies to improve established and emerging spectrum-reliant applications; and second, the requirements for reduced cost, reduced power consumption, and smaller dimensions in RF design, which are driven by consumer market demands (PELEGRINI et al., 2016; MA, 2020). In this context, this work focuses on design methods that include miniaturisation techniques to achieve a Butler matrix design that can operate in the D-band, defined here as frequencies between 110 GHz and 170 GHz.

Figure 4 – Illustrated operation of a Butler matrix.



Source: Author.

1.2 OBJECTIVES OF THIS WORK

This work presents different methods to design a Butler matrix at millimetre-wave frequencies, aiming for wider bandwidth performance and a more compact layout. Two fabrication technologies will be considered: the Metallic-nanowire-Membrane (MnM), and 55-nm BiCMOS, which will be introduced in more detail in Section 1.3 and Section 1.4, respectively. These technologies allow the consideration of trade-offs between cost-effectiveness, fabrication simplicity, level of integration, and technology maturity.

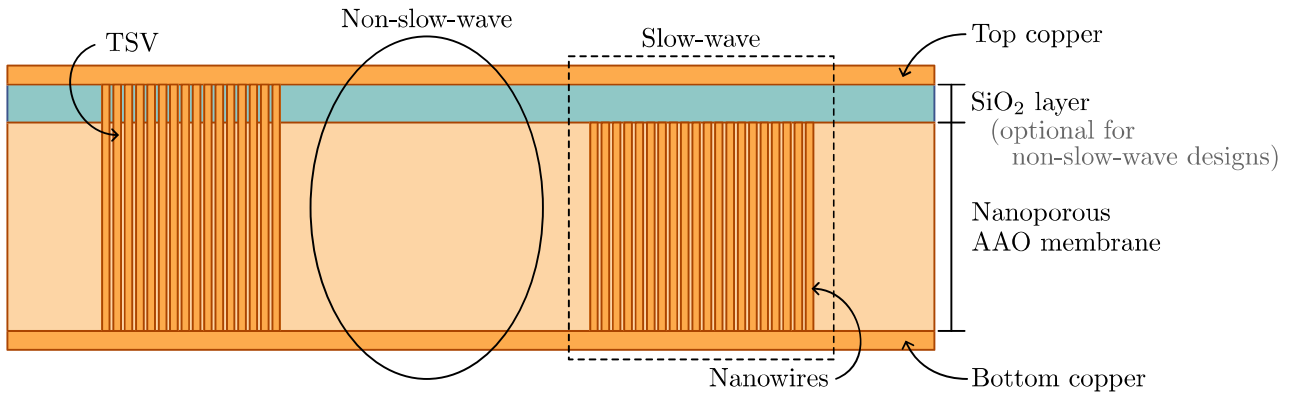
In particular, the objectives of this work include: one, an overview of the foundational concepts involved in the design and analysis of a Butler matrix, conducted through an exploratory design considering MnM technology; two, the design of a miniaturized Butler matrix for operation at the D-band using slow-wave techniques on MnM technology; and three, the design of transdirectional (TRD) couplers on BiCMOS for operation at the D-band, aimed at their use as more compact substitutes to branch-line couplers to achieve a miniaturized Butler matrix, with additional discussion of theoretical perspectives on the use of TRD couplers in other applications due to their unique DC-blocking feature.

1.3 THE METALLIC-NANOWIRE-MEMBRANE TECHNOLOGY

The MnM is a cost-efficient interposer consisting of a nanoporous anodic alumina oxide (AAO) membrane, obtained through electrochemical oxidation of aluminium in specified anodization voltages (PINHEIRO, 2020). It is intended for the design of passive devices, and filling the nanopores with copper to form nanowires allows heterogeneous integration with active devices on a CMOS platform, as exemplified by Pelegri et al. (2016). The MnM technology is comprised of two metal layers, which are 3 μm -thick copper layers, and one or two dielectric layers, which are nanoporous AAO and silicon dioxide (SiO_2), stacked as illustrated in Figure 5. The nanoporous AAO is acquired from InRedox and is available in customisable wafers, where the thickness can be chosen between 20 μm to 150 μm , and pore diameter ranges from 10 nm to 250 nm (INREDOX, 2026). The MnM

technology considered in this work is based on a 50 μm -thick AAO substrate, featuring nanopores with a diameter of 40 nm and spaced 107 nm apart. In the simulations reported in this work, the AAO membrane was modelled with a relative permittivity (ϵ_r) of 6.7 and dielectric loss tangent ($\tan \delta$) of 0.015. Nevertheless, these values come from an electrical characterization of the AAO membrane performed at 60 GHz (PINHEIRO, 2020). Thus, for the D-band, these electrical characteristics may vary, but the values characterized at 60 GHz were still used and considered constant throughout the D-band, as complementary characterization for frequencies above 100 GHz is not yet available. The SiO_2 layer was modelled with $\epsilon_r = 4$, and $\tan \delta = 0$.

Figure 5 – Illustration of the layers constituting the MnM technology, and how they can be used to design TSVs, non-slow-wave structures, and slow-wave structures.



Source: Author.

The process of manufacturing RF circuits and devices using the MnM platform can be summarized as follows: it begins with a cleaning stage, which is followed by deposition of a thin copper film on the backside of the substrate; the front side of the substrate receives a SiO_2 mask patterned by conventional photolithography, allowing selective growth of nanowires; where the substrate is exposed through the SiO_2 , nanowires are grown by electrodeposition of copper; the SiO_2 mask is removed by mechanical polishing, and (optionally, depending on the application) a new SiO_2 layer is deposited by reactive magnetron sputtering; finally, a new copper layer is deposited, patterned and etched according to the device layout (PELEGRINI et al., 2016).

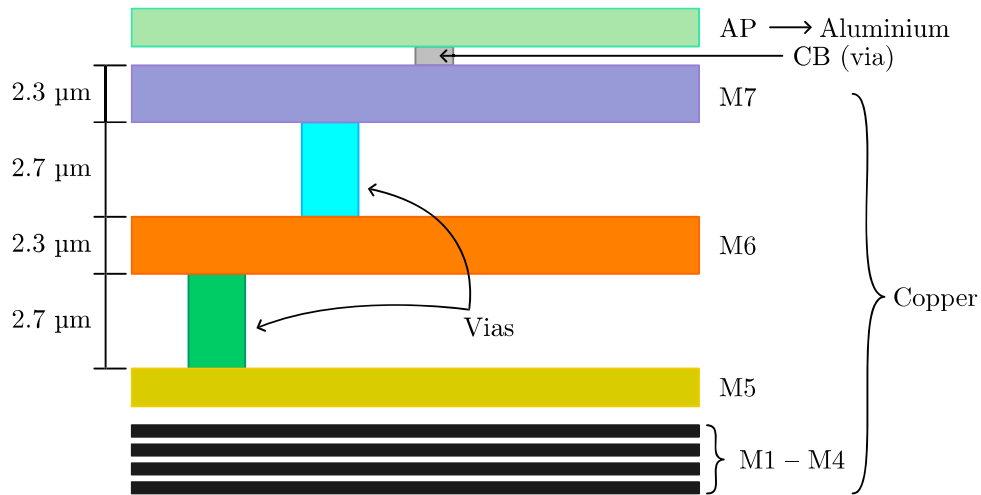
Previous works using MnM technology demonstrated good performance in implementing high-quality transmission lines, through-substrate-vias (TSVs), antennas, impedance transformers, and other passive devices operating at mm-waves. Characterized devices presented good agreement between measured and simulated results (VERONA et al., 2024; PELEGRINI et al., 2016; LÉ et al., 2022; GOMES, 2017).

1.4 THE BICMOS TECHNOLOGY

The technology provided for the design of TRD couplers is the seven-metal-layer 55-nm BiCMOS technology (B55x) from STMicroelectronics, which offers high integrability and versatility, and is capable to support multiple applications with varying cost/performance trade-offs (CHEVALIER et al., 2024a; CHEVALIER et al., 2024b). The metallisation stack for the seven-metal-layer B55x is illustrated in Figure 6. This particular technology features two ultra-thick, one thick, and four thin

copper layers. The thick and ultra-thick metal layers aid in the design of RF transmission lines with satisfactory performance, and the thin metal layers are related to digital performance (CHEVALIER et al., 2024b). Therefore, the analysis presented in this work will consider only the thick and ultra-thick copper layers from the B55x stack, namely, the fifth (M5), sixth (M6), and seventh (M7) metal layers, as well as the topmost aluminium layer (AP) (see Figure 6). Analyses of transmission lines using different combinations of these metal layers as signal and ground are presented on Appendix B.

Figure 6 – Illustration of the metallisation stack for the B55x technology. The dielectric layers that exist in between the metal layers are not drawn here.



Source: Adapted from Chevalier et al. (2024b).

1.5 ORGANIZATION OF THIS DISSERTATION

This dissertation is structured into five chapters. Chapter 1 (this chapter) introduces the motivations and context of the work, outlines the objectives, discusses two key technologies, and cites publications that resulted from parts of this work. Chapter 2 provides an overview of the foundational concepts related to the design and analysis of a Butler matrix. It includes a real implementation of an exploratory design of a Butler matrix on MnM technology and demonstrates the capability of a Butler matrix connected to leaky-wave antennas to provide two-axis beamsteering. Chapter 3 details the methodology for designing a Butler matrix on MnM technology and discusses how to achieve the slow-wave effect with MnM, and how it can be used as a miniaturisation technique to obtain a compact Butler matrix design. The chapter concludes discussing the performance of a complete slow-wave Butler matrix. Chapter 4 presents the design of TRD couplers and their application as compact substitutes to the branch-line coupler, leading to the miniaturization of the Butler matrix. This chapter also presents a preliminary design of a Butler matrix using TRD couplers, estimates its performance through a circuit simulation, and discusses other noteworthy applications of TRD couplers beyond the Butler matrix. Lastly, Chapter 5 concludes the dissertation.

The work described in chapters 2 and 3 was conducted as part of a collaboration with the Millimetre-Wave Centre of the Polytechnic School, São Paulo University, in Brazil, and the work described in Chapter 4 was conducted as part of an internship within TIMA Laboratory, Grenoble Alpes University, in France.

1.6 PUBLICATIONS DERIVED FROM THIS WORK

Several publications have outlined the objectives and findings of this work, as summarized below:

- 2022 – SIMIONATO, E. et al. Design and Analysis of a Butler Matrix at 60 GHz Compatible with Metallic-Nanowire-Filled Membrane Fabrication Platform. In: **XL Simpósio Brasileiro de Telecomunicações e Processamento de Sinais**, 2022. DOI: 10.14209/sbrt.2022.1570824905.

- 2024 – VERONA, B. M. et al. Implementation of a Millimeter-Wave Butler Matrix on Metallic Nanowires-Filled Membrane Platform. In: **IEEE Access**, vol. 12, pp. 22132-22143, 2024, DOI: 10.1109/ACCESS.2024.3357078
- SIMIONATO, E. et al. Design e Análise de Acopladores Transdirecionais Usando Elementos de Parâmetros Concentrados e Linhas Acopladas Serrilhadas. In: **XXI Simpósio Brasileiro de Micro-Ondas e Optoeletrônica (SBMO 2024)**, 2024.
- SIMIONATO, E. et al. Two-axis beamsteering using a wideband Butler matrix and series-fed arrays for millimeter wave frequencies fabricated on metallic-nanowire-membrane platform. **AEU - International Journal of Electronics and Communications**, v. 184, p. 155405, sep. 2024. ISSN 1434-8411

- 2025 – SIMIONATO, E. PENCHEL, R. A. Miniaturização de acoplador híbrido utilizando a técnica de ondas lentas. In: **III Simpósio de Educação, Ciência e Tecnologia da Mantiqueira (SECITEM)**, 2025.
- SIMIONATO, E. et al. D-Band Transdirectional Coupler Employing an Interdigital Capacitor Structure in 55-nm BiCMOS. In: **2025 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)**, Campina Grande, Brazil, 2025, pp. 801-805, DOI: 10.1109/IMOC65414.2025.11365701.

5 CONCLUSIONS

This work was undertaken to explore design methods for the Butler matrix at millimetre-wave frequencies, motivated by the use of beamforming networks at extremely high frequencies to improve established and emerging spectrum-reliant applications. This work focused in particular on novel design methods capable of miniaturisation, motivated by requirements for reduced cost and compact designs driven by consumer market demands.

First, foundational concepts involved in the design and analysis of a Butler matrix were presented and the traditional design method was studied through the analysis of an exploratory design of the Butler matrix. It was also shown through the exploratory design that the Butler matrix can provide two-axis beamsteering when combined with leaky-wave antennas. Then, two miniaturisation-focused design methods were analysed at the D-band and discussed: one employing the slow-wave technique, and the other based on TRD couplers.

The slow-wave Butler matrix considered the MnM technology, where nanowires facilitate the slow-wave effect, thereby providing miniaturisation by lowering the phase velocity of the wave propagating through the slow-wave structure. This design achieved matched inputs ($|S_{nn}| < -10$ dB) for a 18.5% fractional bandwidth, which is comparable to the performance of the exploratory design that presented a 17.8% fractional bandwidth for this criteria. However, the slow-wave matrix exhibited greater amplitude unbalance between the outputs, and larger phase deviations from the ideal values. Nevertheless, the slow-wave technique led to a device that occupied only 7.2% of the area of the exploratory design (a 92.8% reduction).

It was shown that TRD couplers can be more compact substitutes to the branch-line couplers used in the design of a Butler matrix, leading to a miniaturised design. However, slow-wave coupled lines on MnM could not reach tight coupling coefficients and were insufficient to design a 3-dB coupler. Thus, TRD couplers were designed on BiCMOS in two different implementations, each catering to different design requirements, but together enabling the design of millimetre-wave TRD couplers with port impedance ranging from $5\ \Omega$ to more than $80\ \Omega$, coupling between 20 dB and 0.9 dB, and varied levels of compactness. The preliminary circuitual design of a Butler matrix with TRD couplers achieved the widest fractional bandwidth for which $|S_{nn}| < -10$ dB, at 46.3%, more than double that of the other two designs. The amplitude unbalance between the outputs for the matrix with TRD couplers was close to that of the exploratory design, but the phase deviation from the ideal values was comparable to the slow-wave design, significantly larger than that of the exploratory design. Notably, the estimated area occupied by TRD-coupler-based Butler matrix is only 0.6% of the area occupied by the exploratory design (a 99.4% reduction).

To summarise the significance of this work for the state-of-the-art, the present study has demonstrated, for the first time, a slow-wave Butler matrix and TRD couplers operating at the higher end of millimetre-wave frequencies. It further contributes to the body of knowledge by discussing Butler matrix design methods considering two technologies: the MnM platform, whose development aims to provide heterogeneous integration, greater fabrication simplicity and lower cost compared with the BiCMOS technology, a mature and commercially available technology offering high integrability.

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