UNIVERSITI TEKNOLOGI MARA

DEVELOPMENT OF COMPACT DUAL-LAYER 4×4 BUTLER MATRIX FOR SUB-6GHZ MULTIBEAM APPLICATIONS

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ABSTRACT

The rapid deployment of fifth-generation (5G) communication systems in the sub-6 GHz band demands compact, low-loss, and phase-accurate multibeam antenna solutions for base station applications. Conventional 4×4 Butler Matrix (BM) beamforming networks, although structurally simple, suffer from large physical footprint (100 mm × 120 mm, equivalent to $2.38\lambda^2$), routing congestion due to crossover elements, and phase sensitivity that limits compact antenna integration. This thesis presents the systematic development of a compact dual-layer 4×4 Butler Matrix integrated with a 1×4 linear microstrip antenna array operating at 3.5 GHz. The research begins with the design of a modified single-layer 4×4 Butler Matrix, achieving a reduced footprint of 112.46 mm × 94.2 mm while maintaining accurate phase progression. The simulated phase deviation was limited to an average of 1.57° with a maximum error of 3.52°, well within the ±5° tolerance required for stable beamforming. However, further miniaturization was pursued through a novel stacked dual-layer architecture employing via-hole optimization and subsequent crossover elimination. By removing the 0 dB crossover and implementing vertical interlayer routing, the final compact configuration achieved a physical dimension of 94.20 mm × 63.62 mm (5,993 mm²), corresponding to approximately 50% reduction in physical area compared to the conventional 12,000 mm² design. In normalized electrical terms, the footprint was reduced from $2.38\lambda^2$ to $0.814\lambda^2$, representing a 65.8% reduction in electrical size without frequency scaling. The number of functional components was reduced from ten to six, simplifying routing complexity while preserving amplitude balance and progressive phase characteristics. Measured S-parameter results demonstrated strong impedance matching, with input return loss reaching −30 dB and consistently remaining below −20 dB at 3.5 GHz. The matrix-maintained isolation levels better than −15 dB between adjacent ports. The dual-layer configuration achieved a 19.11% fractional bandwidth (634 MHz) centered at 3.5 GHz, covering the required 5G mid-band range. The optimized Butler Matrix was integrated with a 1×4 linear microstrip antenna array with 0.58λ (50 mm) inter-element spacing. The standalone patch element achieved a peak gain of 4.13 dBi and a half-power beamwidth (HPBW) of 73.8°. When fully integrated, the multibeam antenna system successfully generated four distinct beams. The measured main beam directions were −16°, −46°, 16°, and 46°, closely matching theoretical and simulated predictions. The measured mutual coupling between input ports remained below −15 dB, and all input ports exhibited return loss better than −13.95 dB at 3.5 GHz. The proposed architecture demonstrates that substantial miniaturization can be achieved through structural optimization rather than dielectric scaling or metamaterial loading, thereby avoiding additional loss mechanisms and fabrication complexity. Phase sensitivity analysis further confirms that the compact dual-layer topology maintains beam pointing stability under amplitude and phase perturbations. Overall, this research establishes a compact, crossover-free, and phase-stable 4×4 Butler Matrix architecture that achieves significant size reduction, wide operational bandwidth, low insertion loss, accurate phase progression, and validated multibeam performance. The developed system provides a practical and fabrication-friendly solution for sub-6 GHz 5G small-cell base station deployment and contributes a scalable framework for future compact passive beamforming networks.

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CHAPTER 1
INTRODUCTION

1.1 Research Background

The evolution of mobile communication networks from earlier generations to fifth-generation (5G) systems reflects a transformative shift in performance expectations and infrastructure design. Unlike legacy systems that primarily focused on voice and moderate data services, modern wireless networks are required to support ultra-high data rates, massive connectivity, ultra-low latency, and reliable communication in highly dynamic environments. As illustrated by the progression from 1G to 5G as shown in Figure 1.1, peak data rates have increased dramatically from kilobits per second in early systems to multi-gigabit-per-second capability in 5G driven by exponential growth in connected devices and data-intensive applications [1].

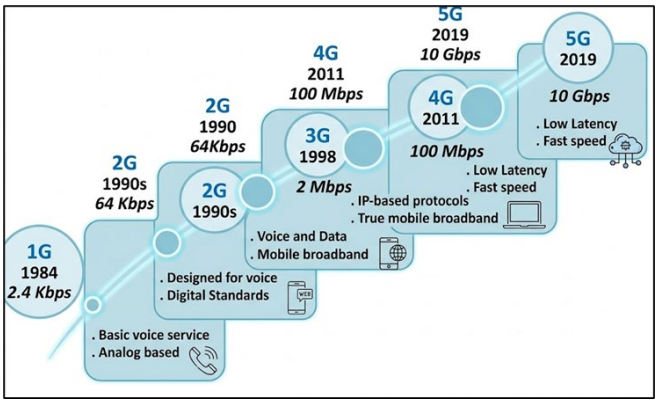

Figure 1.1 Evolution of Mobile Communication Networks [1]

Modern 5G deployment must address highly challenging operational scenarios, including dense residential areas, stadiums with millions of connections per square kilometre, open-air mass gatherings, underground transportation systems, high-speed mobility environments, and wide-area suburban coverage [2]. These scenarios demand not only increased system capacity and bandwidth but also intelligent spatial resource management. In particular, Sub-6 GHz frequency bands play a crucial role in 5G infrastructure due to their favourable propagation characteristics, enabling reliable coverage while supporting high data throughput [3]. However, the limited spectral