Hybrid Ring-Mesh Topology of Fifth Generation (5G) Small Cells for Energy Optimization of Millimetre-Wave Backhaul

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ABSTRACT

Small cells are positioned as a complementary solution to the existing cellular infrastructure, rather than a complete replacement. However, densification of cells leads to an exponential rise in power consumption, especially in the backhaul segment connecting the small cells. Adopting mm Wave spectrum with a vast bandwidth for wireless backhaul links can provide multi-gigabit capacity through intelligent network design. Hence, the paper presents a hybrid backhaul architecture combining ring topologies with mesh interconnects' flexibility using mmWave technology. The methodology developed the hybrid ring-mesh (HRM) topology adaptation spanning the physical link and network layers. The optimization problem formulation used a bio-inspired firefly algorithm embedded in the MATLAB/Simulink environment. The result showed that HRM topology has the highest throughput of 900Mbps and is fastest compared to Ring and Star topologies of 300Mbps and 500Mbps, respectively. It maximizes energy efficiency from 30Mbps/W and 50Mbps/W of Ring and Star topologies to 90Mbps/W and a latency of approximately 0.5ms. The study provides an alternative means for mm Wave backhauling of small cells as it maximizes energy efficiency while ensuring stringent quality of service (QoS) and also offers considerable throughput and latency where there are few number of small cell base stations.

INTRODUCTION

The emergence of 5G networks stands as a new age of wireless communication that will revolutionize next-generation networks, delivering extraordinary features such as enhanced data rates, massive machine-type connectivity and ultra-reliable low-latency communications (Andrews *et al*., 2014; Frenger *et al*., 2020). This next generation of wireless networks is on the threshold to transform various industries and support many applications, from the evolution of mobile broadband to Virtual Reality to smart infrastructure monitoring to control of self-driving cars. (Ericsson, 2020; Shafi *et al*., 2017).

The very essence of the 5G vision is based on the densification of the physical infrastructure in the form of the low power-consuming small cell networks – localized base stations targeted for specific areas (Andrews *et al*., 2014; Abolade *et al.,* 2022). As the need for data increases at an exponential rate due to factors such as the emergence of smart devices and bandwidth-intensive applications, mobile operators are now seeking the use of small cells as a cost-efficient solution towards increasing network capacity and improving user experience (Taori and Sridharan, 2015; Ericsson, 2020).

In the 5G system design, innovative technologies are introduced in the radio access network (RAN) and core network (CN) to achieve the performance goals of the 5G wireless networks. The RAN, which supports wireless connection and mobility management functions, utilizes some advanced technologies to meet the intended enhancement of traffic capability by 1000X and data rate by 100X, respectively (Andrews *et al.*, 2014; Frenger *et al*., 2020). One of the key enablers in the RAN is the application of high-frequency bands like 28 GHz and 73 GHz, better known as the millimeter wave (mmWave) spectrum, which offers considerably wider bandwidth compared with the typical cellular frequency bands. By using these previous marginal zones of the radio frequency spectrum, 5G networks can provide immense opportunities to cover the constantly growing demand for traffic capacity.

In addition to mm Wave spectrum, the 5G RAN acts through small cell densification where traditional macro cells are supported by numerous small, low-power Base Stations (Loch, 2015; Andrews *et al.,* 2014; Iqbal *et al*., 2020). This approach not only advances the network towards users with better signal strength and less path loss but also leads to better frequency reuse and high space division multiplexing (Taori and Sridharan, 2015). However, with the dense deployment of small cells, several hurdles come into play, such as backhauling limitations, mobility management, synchronization, and energy efficiency issues (Frenger *et al*., 2020; Chen *et al*., 2020). Therefore, this work aimed to design an energy-optimized hybrid ring-mesh backhaul topology for 5G mmWave small cells.

REVIEW OF RELATED WORKS

This section presents a review of related works about 5G small cells and backhaul topologies. Polese *et al.* (2022) proposed dynamic routing algorithms in mmWave mesh networks, adapting to blockage patterns, showing 20% throughput gains. The central controller tracks obstruction analytics to model spatial blockage risks, tuning redundant path likelihoods, balancing reliability and efficiency. Shi *et al.* (2021) developed a topology switching model between chains and rings, handling dynamic traffic balancing through redundancy promises appreciable power savings. The algorithm utilizes runtime traffic indicators from the FBMC PHY layer to actuate transitions between ring and chain modes, minimizing stranded capacity and enhancing energy proportionality.

Jiang *et al.,* (2020) implement joint small cell backhaul and access control algorithms, improving experienced reliability by 21% from coupling effects. By unifying client association policies and wireless routing path switching through common KPI analytics, significant coupling gains emerge, exceeding standalone optimization scope through rapid local adaptivity. Shojaeifard *et al.* (2018) quantify the impact of architectural advances like hybrid beamforming for 5G backhauling capacity through modeling. Adaptive digital pre-coding and specification of optimal phase shifter bit widths guide implementation cost analysis, balancing link budgets for availability targets, helping RF system synthesis.

METHODOLOGY

This section illustrates the quantitative methodology used to model and evaluate the hybrid ring-mesh backhaul topology adapted for 5G mm Wave small cells targeting enhancements in energy efficiency. The hybrid topology leverages intersections of mesh networks and ring assemblies for realizing reliability and efficiency benefits. As shown in Figure 1, the backhaul network cluster consists of 10 nodes in a partial mesh pattern with redundant interlinks between selected nodes for path diversity. The nodes and links are labelled with block and small letters, respectively.

This provides adaptable multi-connectivity subject to active link choices. Overlaid are two redundant fiber rings created using optical add-drop multiplexers, providing speed and capacity benefits, harnessing exclusivity while mesh fabric delivers reliability. The dimensions can be parameterized by controlling hybridization factors.

In a Ring-Mesh topology, nodes are connected in a circular fashion (ring) while also having multiple connections (mesh) to other nodes. Each node is connected to two other nodes in the ring and can have additional connections to other nodes, forming a mesh. The mesh aspect allows for multiple pathways for data, improving fault tolerance. Also, data can travel in both directions around the ring, which can enhance speed and reliability. Firefly optimization algorithm was adopted to enhance energy efficiency in the hybrid backhaul topology, leveraging mathematical programming. The optimization problem formulation employed a bio-inspired firefly algorithm, which provides a heuristic solution integrated into a MATLAB/Simulink simulation environment.

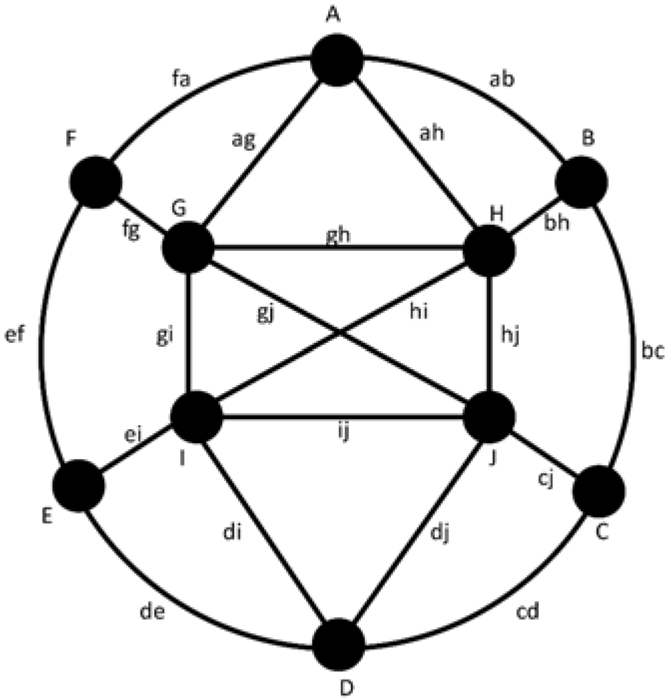

Figure 1: The architecture of the hybrid ring-mesh topology

PERFORMANCE METRICS DEFINITION

Quantified KPIs for benchmarking enhancements span across power efficiency, quality of service, resilience and reliability indicators as captured mathematically through equations (1) to (4) covering key metrics - total power, mean delay, drop rates and disruption time:

$$P_{total} = \sum_{i=1}^{N} P_i + \sum_{j=1}^{L} P_j \quad (1)$$

$$\text{AQA}D_{mean} = \sum_{i=1}^{\{M\}} d_i \times \sum_{\{t=1\}}^{\{T\}} \frac{M}{c.T} \quad (2)$$

$$Drop\ Rate = \frac{Lost\ packets}{Generated\ packets} \quad (3)$$

$$Disruption\ Time = \sum_{i=1}^{F} \frac{r_i}{s_i} \times F \quad (4)$$

Where,

N and L are the number of nodes and links, with P denoting individual power profiles.

M flows across T time slots, indicating a delay d

Drop rate calculated using lost and generated packets

Disruption duration is the difference between failure start/stop instances.

RESULT AND DISCUSSIONS

The analysis in Figures 2 and 3 reveals that throughput and energy efficiency decrease with more SBS, suggesting that adding more SBS reduces the overall energy efficiency of the network. Figures 4 and 5 show the relationship between latency and packet delay ratio (PDR) concerning small cell Base Stations (SBS). However, Figures 6 and 7 show the comparative evaluation between ring, star and ring-mesh topology of small cells and it was established that ring-mesh topology performed better than the conventional star and ring topology in terms of latency, throughput, packet delay ratio (PDR) and energy efficiency. The result showed that at 100% LOS, the Hybrid Ring-Mesh topology has the highest throughput of 900 Mbps and is fastest compared to Ring and Star topologies of 300 Mbps and 500 Mbps, respectively. It maximizes energy efficiency to 90Mbps/W from 30Mbps/W and 50Mbps/W of Ring and Star topologies, and a latency of approximately 0.5ms. The study provides an alternative means for mmWave backhauling of small cells as it maximizes energy efficiency while ensuring a stringent quality of service (QoS) and also offers considerable throughput and latency where there is a smaller number of small cell base stations.

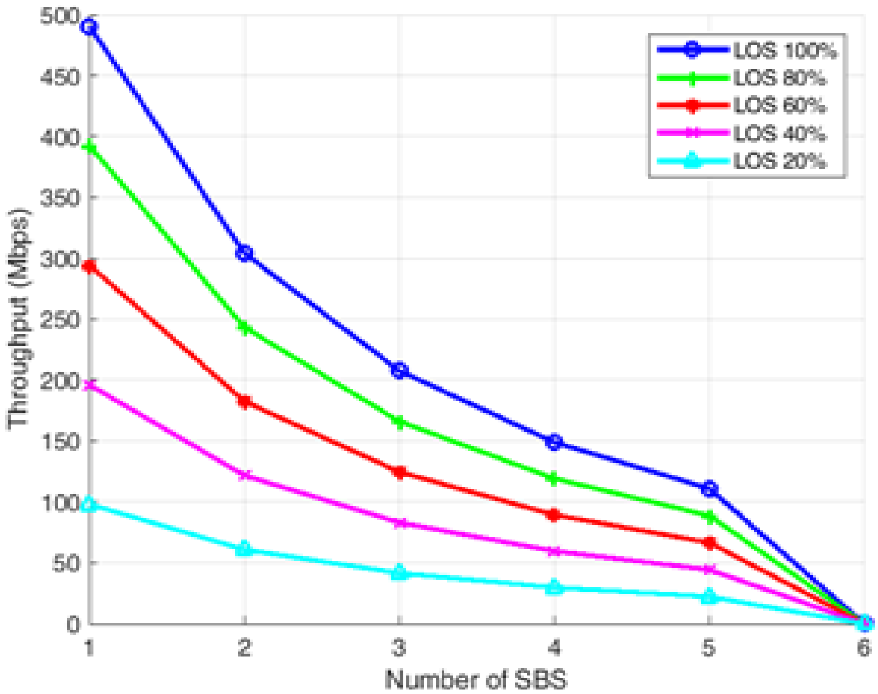

Figure 2: Relationship between throughput and Small Cell Base Stations (SBSs).

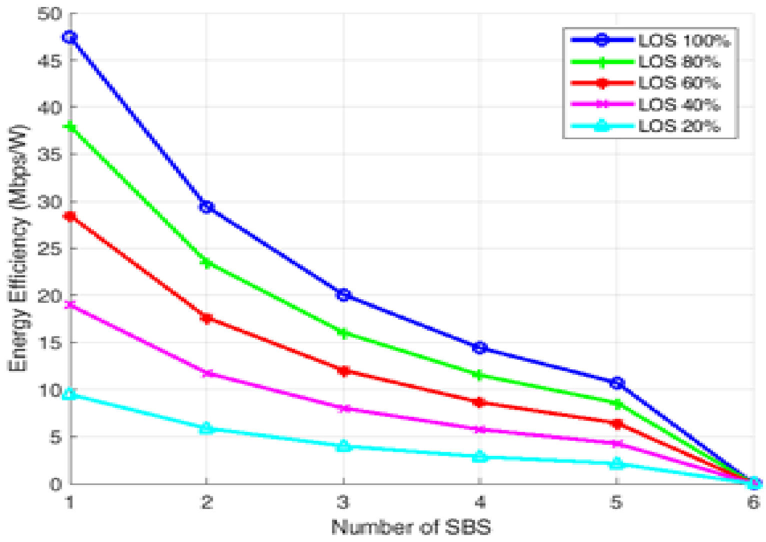

Figure 3: Relationship between Energy Efficiency and Number of Small Base Stations (SBS)

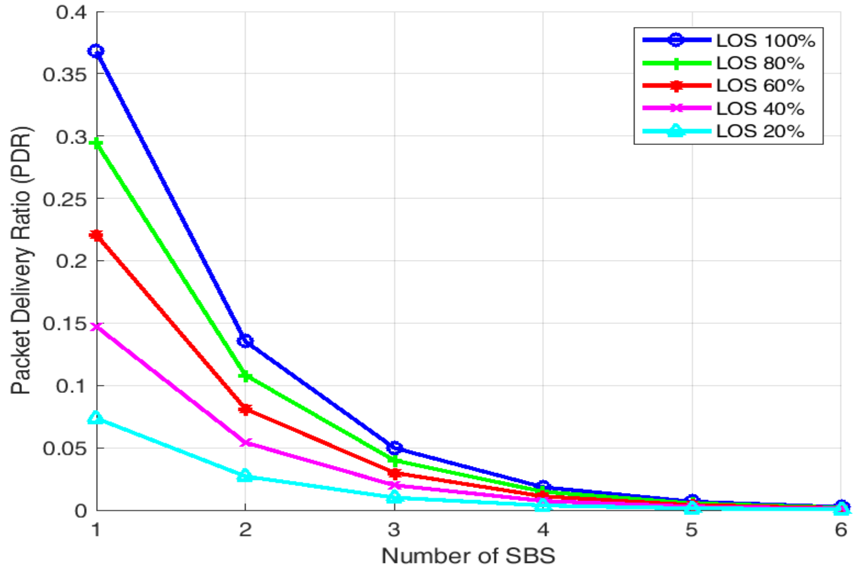

Figure 4: Relationship between Packet Delay Ratio (PDR) and Number of Small Base Stations (SBS)

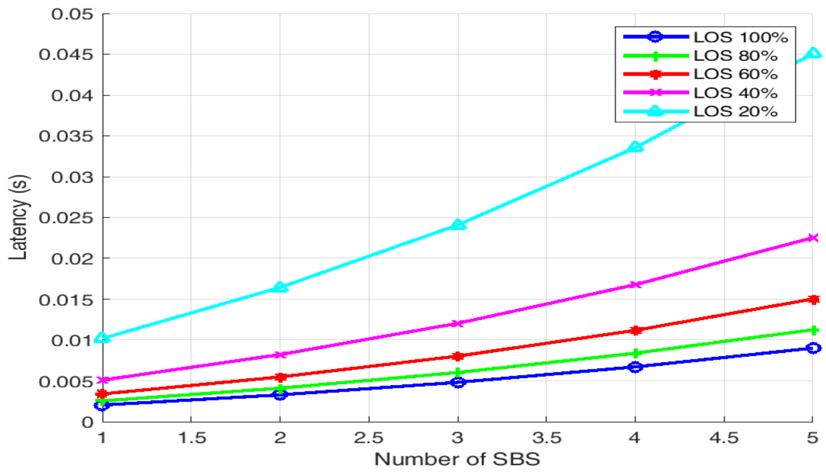

Figure 5: Relationship between Latency and Number of Small Base Stations (SBS)

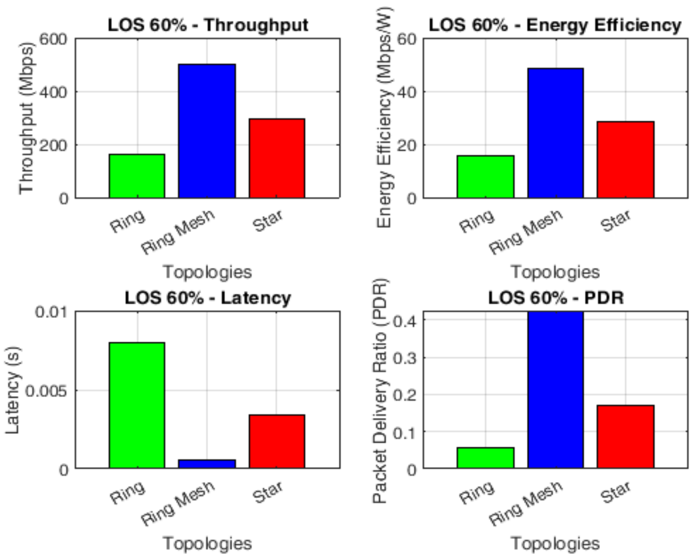

Figure 6: Comparison of Three Topologies using Parameters at 60% Line-of-Sight (LOS)

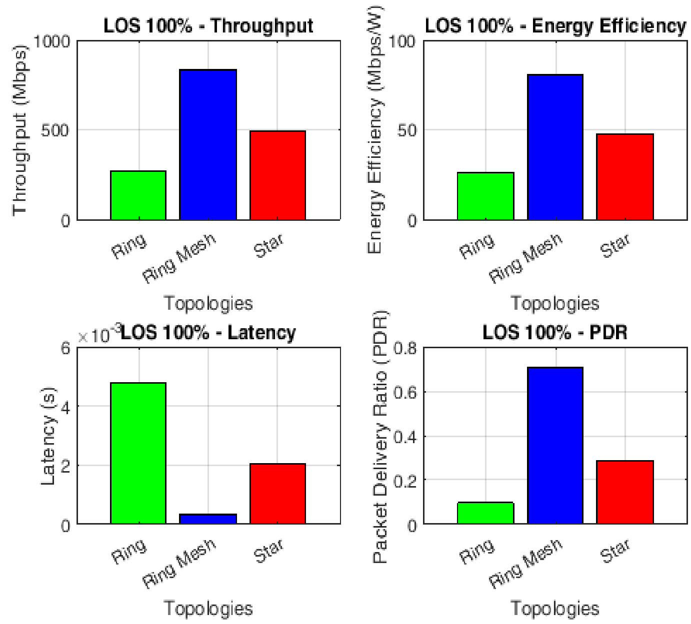

Figure 7: Comparison of Three Topologies using Parameters at 100% Line-of-Sight (LOS)

CONCLUSION

In conclusion, after executing simulations across the different backhaul topologies using aligned configuration settings, performance results that allow standardized comparative analysis were obtained. This benchmarking-based comparative methodology revealed meaningful insights on the relative merits of the hybrid ring-mesh backhaul in delivering energy-efficient 5G small cell connectivity.

REFERENCES

Abolade, J. O., Konditi, D. B., Mpele, P. M., Orimogunje, A. M., and Oguntoye, J. P. (2022). Miniaturized dual-band antenna for GSM1800, WLAN, and sub-6 GHz 5G portable mobile devices. *Journal of Electrical and Computer Engineering*, *2022*(1), 5455915.

Andrews, J.G., Buzzi, S., Choi, W., Hanly, S.V., Lozano, A., Soong, A.C., and Zhang, J.C. (2014). What will 5G be? *IEEE Journal on Selected Areas in Communications*, 32(6), 1065-1082.

Chen, M., Zhang, Y., Hu, L., Taleb, T., and Sheng, Z. (2020). Cloud-based wireless network: Virtualized, reconfigurable, smart wireless network to enable 5G technologies. *Mobile Networks and Applications*, 25(4), 1191-1212.

Frenger, P., Meyer, J., Hellsten, T., Olsson, M., Alriksson, P., Eriksson, K., and Parkvall, S. (2020). Towards a better user experience in 5G networks: Factors to consider. *IEEE Vehicular Technology Magazine*, 15(4), 72-81.

Iqbal, M.S., Bolen, T., Thakolsri, S., Grundström, P., and Wikström, G. (2020). Wireless backhaul node consolidation in 5G CHASE relay networks. *IEEE Access*, 8, 165460-165471.

Jiang, Y., Bu, C., Zhu, W., and Yang, L. (2020). Coordinated client association and wireless backhaul routing for massive, scalable mmWave networks. *IEEE Transactions on Communications*, 68(9), 5415-5430.

Polese, M., Mezzavilla, M., Dore, M., Kirev, D., Bor-Yaliniz, I., Eckhardt, H., and Rangan, S. (2020). Understanding millimetre-wave networking for future indoor environments. *In 2020 IEEE Wireless Communications and Networking Conference (WCNC)* (pp. 1-6). IEEE.

Shafi, M., Molisch, A.F., Smith, P.J., Haustein, T., Zhu, P., De Silva, P., and Kåredal, J. (2017). 5G: A tutorial overview of standards, trials, challenges, deployment, and practice. *IEEE Journal on Selected Areas in Communications*, 35(6), 1201-1221.

Shi, X., Zhang, Y., Wang, H., Liu, Y. and Chen, Y. (2021). A new Topology-switching Strategy for Fault Diagnosis of Multi-Agent Systems based on Belief Rule Base. *IEEE Transactions on Automatic Control*, 66(12), 6789-6802.

Shojaeifard, A., Xie, H., Tao, H., Svensson, T., and Hoshyar, R. (2020). Millimeter-wave phased array antennas for wireless backhaul systems: Prototyping and experimental analysis. *IEEE Access*, 8, 107046-107058.

Taori, R., and Sridharan, A. (2015). In-Band, Point-To-Multi-Point, mm-Wave Backhaul For 5G Networks. *IEEE International Conference on Communications Workshops (ICC).*