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Hybridization of Ring and Mesh Topologies in Fifth Generation (5g) Small Cells for Energy Optimisation 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 the reliability of ring topologies with the flexibility of mesh interconnects using mmWave technology. The methodology developed the hybrid ring-mesh (HRM) topology adaptation spanning the physical link and network layers. The optimisation problem formulation used a bio-inspired firefly algorithm and was embedded in 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 500 Mbps, respectively. It maximises 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 maximises energy efficiency while ensuring stringent quality of service (QoS) and also offers considerable throughput and latency where there is few number of small cell base stations.

INTRODUCTION

The advent of fifth-generation (5G) wireless networks signifies a transformative shift in mobile communications, offering capabilities such as ultra-reliable low-latency communication (URLLC), enhanced mobile broadband (eMBB), and massive machine-type communication (mMTC) (Andrews et al., 2014; Frenger et al., 2020). These advances are driven largely by small cell densification and the utilisation of millimetre-wave (mmWave) spectrum bands, particularly those at 28 GHz and 73 GHz, which offer substantial bandwidth resources capable of supporting multi-gigabit data rates and vast user densities. Despite these benefits, communication at mmWave frequencies is severely constrained by high path loss, limited diffraction, and a heavy reliance on line-of-sight (LOS) transmission. These limitations necessitate dense deployments of small cells to ensure consistent and reliable coverage, especially in urban or obstructed environments. Such densification, in turn, imposes significant demand on the backhaul network—the infrastructure responsible for linking distributed small cell base stations to the core network.

Within the 5G system architecture, innovations are implemented at both the radio access network (RAN) and the core network (CN) levels to meet ambitious performance objectives. The RAN, which is responsible for wireless connectivity and mobility management, incorporates advanced transmission technologies to achieve enhancements of up to 1000 times in traffic capacity and 100 times in peak data rates relative to previous generations (Andrews et al., 2014; Frenger et al., 2020). However, these improvements at the access layer can only be fully realised if matched by a backhaul infrastructure that is equally capable, energy-efficient, and resilient under dynamic network conditions.

Traditional backhaul architectures such as star and ring topologies present considerable limitations in meeting 5G's stringent Quality of Service (QoS) demands. Star configurations are vulnerable to single points of failure, while ring structures, though more resilient, provide only limited path diversity. Fully meshed networks improve reliability and fault tolerance but come at the cost of increased complexity, redundancy, and control overhead.

In light of these limitations, this research proposes a hybrid ring-mesh (HRM) backhaul topology designed specifically for the mmWave-based 5G small cell environment. The study explores how such a topology can be effectively modelled and dynamically optimised to improve throughput, reduce latency, and maximise energy efficiency. The hybrid architecture aims to exploit the path diversity and fault tolerance of mesh networks while preserving the structured reliability and lower complexity of ring-based systems. In doing so, the research addresses the critical challenge of designing an adaptive, resilient, and power-efficient backhaul solution capable of supporting the evolving demands of 5G wireless systems, particularly under varying LOS conditions.

This research presents several key contributions to the field of 5G mmWave small cell networks. It introduces a hybrid ring-mesh backhaul topology specifically designed to enhance the performance and reliability of such networks. To optimize routing with minimal energy consumption, a bio-inspired Firefly Algorithm is integrated, enabling dynamic and adaptive path selection. The proposed system is rigorously evaluated through MATLAB/Simulink simulations, with a particular focus on how variations in line-of-sight conditions affect critical performance metrics such as throughput, latency, and Packet Delivery Ratio (PDR). Additionally, the hybrid topology is benchmarked against traditional star and ring configurations under both aligned and varied line-of-sight scenarios to demonstrate its superiority in diverse deployment conditions.

METHODOLOGY

This study was executed in two key phases, each corresponding to the stated research objectives: (1) modelling a hybrid ring-mesh (HRM) backhaul topology tailored to the architectural requirements of 5G millimetre-wave (mmWave) small cell networks, and (2) implementing an optimisation framework to enhance the topology's energy efficiency using bio-inspired algorithms.

Modelling the Hybrid Ring-Mesh Topology

The first phase focused on the design and simulation of a backhaul network architecture that leverages the structural and performance benefits of both ring and mesh configurations. The network was conceptualised as a hybrid model comprising a circular ring interconnection among small cell base stations (SBS), augmented with selective mesh links for redundancy and fault tolerance.

A total of ten nodes were positioned in a partially meshed topology, wherein each node maintained a standard ring connection to two neighbouring nodes and supplementary links to strategically selected peers, forming a hybrid connectivity pattern. The network layout, as illustrated in Figure 1, was parameterised with adjustable "hybridisation factors" to control the density and diversity of mesh interlinks.

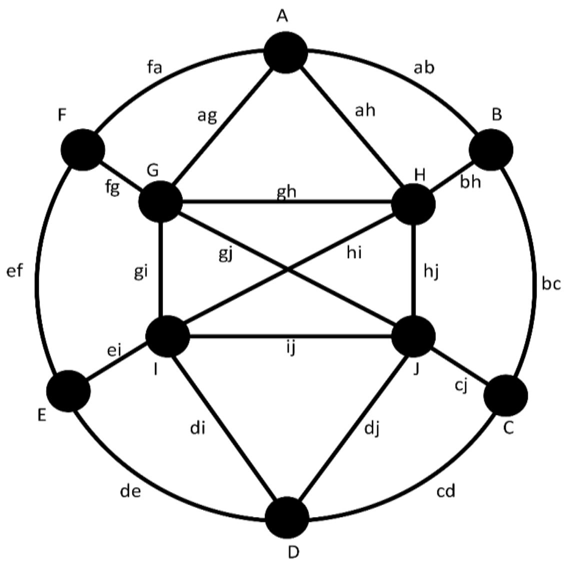

Figure 1. The architecture of a hybrid ring-mesh topology.

To ensure high-capacity and low-latency transmission, dual concentric fibre rings were overlaid across the mesh fabric using optical add-drop multiplexers (OADMs). These fibre rings provided exclusive high-speed links while the mesh layer contributed robustness and multiple path options. Network abstractions followed the standard Open Systems Interconnection (OSI) stack, linking LTE radio access components to the HRM backhaul via gateway anchors.

At the transport layer, retransmission strategies and TCP window adaptation mechanisms were modelled to reflect reliability-centric behaviour. Routing was handled by latency-aware multipath protocols adapted from the Open Shortest Path First – Traffic Engineering (OSPF-TE) algorithm, which exploited the redundant links within the hybrid mesh to optimise data flows. Traffic classification and service differentiation were implemented using queuing models at the network and data link layers, allowing real-time, best-effort, and bulk services to coexist with prioritised handling.

Energy Optimisation Using the Firefly Algorithm

The second phase involved the development and application of an energy-efficient optimisation model for the HRM topology. The goal was to minimise overall power consumption in the backhaul network while satisfying key Quality of Service (QoS) requirements such as throughput, latency, and packet delivery ratio (PDR).

A constraint-based routing and scheduling problem was formulated, where each routing decision was subject to power budget limitations and QoS thresholds. This optimisation problem was solved using the Firefly Algorithm (FA), a nature-inspired metaheuristic based on the flashing behaviour of fireflies in search of optimal mates or food sources.

The Firefly Algorithm was implemented as a series of functional blocks within MATLAB and integrated into the Simulink simulation environment. The algorithm was invoked dynamically through runtime triggers managed by a transport-layer controller, which monitored real-time network conditions such as traffic variation and LOS (line-of-sight) degradation. The controller periodically initiated FA-based routing updates and scheduling decisions to adaptively reconfigure network paths in response to environmental changes.

Each firefly in the population represented a candidate routing configuration. The brightness of a firefly was determined by a fitness function combining throughput performance and power consumption. Fireflies moved toward brighter neighbours based on an attractiveness function inversely proportional to their distance, enabling convergence toward highly energy-efficient routing schemes. Algorithmic parameters such as step size, light absorption coefficient, and randomisation factor were tuned for convergence speed and solution diversity.

Simulations were conducted across five LOS probability levels (1.0, 0.8, 0.6, 0.4, and 0.2) to evaluate performance under varying real-world conditions. For each scenario, the HRM topology's performance was benchmarked against conventional ring and star topologies. Metrics such as throughput, energy efficiency (Mbps/W), latency (ms), and PDR (%) were recorded and compared across the different configurations.

Algorithm for mmWave Backhaul Network Simulation

Initialization:

i. Define the parameters such as the number of nodes, distance between nodes, frequency, transmit power, noise figure, bandwidth, antenna gain, system loss, circuit power, and power amplifier efficiency.

ii. Set the LOS probabilities and topologies (Star, Ring, Ring-Mesh).

iii. Initialize storage for all metrics (Throughput, Energy Efficiency, Latency, PDR).

Iterate Over Each Topology:

i. Star Topology: Calculate distances based on a central node connecting to all other nodes.

ii. Ring Topology: Calculate distances between adjacent nodes forming a loop.

iii. Ring-Mesh Topology: Calculate distances with reduced distance between nodes and improved parameters (increased antenna gain, reduced noise figure

For Each Topology and LOS Probability:

i. Calculate SNR: Use the transmit power, antenna gain, system loss, noise figure, and bandwidth to compute the Signal-to-Noise Ratio (SNR).

ii. Calculate Throughput: Use the SNR and LOS probability to compute the throughput.

iii. Calculate Energy Efficiency: Compute the energy efficiency using throughput, transmit power, circuit power, and power amplifier efficiency.

iv. Calculate Latency: Compute latency as the inverse of throughput; reduce latency for the Ring Mesh topology.

v. Calculate PDR: Compute the Packet Delivery Ratio based on the distance and LOS probability; improve PDR for the Ring-Mesh topology.

Store Results:

Store the computed metrics for Throughput, Energy Efficiency, Latency, and PDR.

Plot Results:

Generate grouped bar charts for each LOS probability, displaying metrics across topologies:

i. Throughput
ii. Energy Efficiency
iii. Latency
iv. PDR

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:

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

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

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

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

where N and L are the number of nodes and links, with P denoting individual power profiles. M flows across T time slots, indicating delay d. Drop rate calculated using lost and generated packets.

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

These equations are not only used in simulations but also underpin the evaluation of optimization effectiveness. For instance, lower Ptotal indicates better energy efficiency, while reduced D and higher Packet Delivery Ratio (PDR) reflect improved Quality of Service (QoS).

Benchmarking Setups

To evaluate the effectiveness of the proposed hybrid ring-mesh backhaul topology and energy optimization approach, its performance was evaluated against other backhaul architectures. Specifically, the following benchmark networks were modelled and simulated:

1. Conventional Star-based topology for small cell backhaul

2. Ring-based backhaul architecture

These represent commonly studied backhaul topologies in research literature and industry standards. Table 1 shows the system simulation parameters. For fair comparison, we configured the simulation parameters including traffic profiles, scheduling schemes, power models etc. to be identical across the different backhaul architectures.

The key QoS and efficiency metrics compared and contrasted were:

Latency: Total Latency is given as;

$$T_L = T_t + T_p + T_q + T_{pr} \quad (5)$$

Where : T_t = Transmission Delay

T_p = Propagation Delay

T_q = Queuing Delay

T_{pr} = Processing Delay

Throughput: This formula calculates the throughput in bits per second (bps) based on the Shannon-Hartley theorem.

$$Throughput = bandwidth * log2(1 + 10^{(snr/10)}) * los\_probability \quad (6)$$

Where, bandwidth: Bandwidth of the signal (in Hz), Snr is the signal-to-Noise Ratio, converted from dB to linear scale and los_probability is the probability of a line-of-sight (LOS) path being present, used as a scaling factor.

Table 1: System Simulation Parameters

S/N	Parameters	Specifications
1	Nodes	10
2	Distance between nodes	500 metres
3	Frequency	28 GHz
4	Transmitting power	20 dBm
5	Noise figure	5 dB
6	Bandwidth	100 MHz
7	Antenna gain	30 dBi
8	System loss	3dB
9	Speed of light	3×10^8m/s
10	LOS probabilities	1.0, 0.8, 0.6, 0.4, 0.2

Packet Delivery Ratio (PDR): Packet Delivery Ratio (PDR) is given as ;

$$pdr = los\_p * exp\left(\frac{-x_d}{800}\right) \quad (7)$$

Where, los_p is the probability of a line-of-sight (LOS) path and x_d is the distance between the transmitter and receiver (in meters).

Energy efficiency:

$$energy\_efficiency = \frac{throughput}{power\_consumption} \quad (8)$$

Where throughput is the data rate or the number of bits transmitted per second (in Mbps), power_consumption is the total power consumption in the system, including transmit power and circuit power.

Comparative Evaluation

By executing simulations across the different backhaul topologies using aligned configuration settings, performance results that allow standardized comparative analysis was obtained. The following qualitative and quantitative contrasting of metrics was done:

i. Numerical comparison of metrics values across solutions
ii. Normalization techniques (e.g. per byte energy efficiency)
iii. Statistical significance testing between architectures
iv. Graphical visualization using performance curves.

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.

RESULTS AND DISCUSSION

The hybrid Ring Topology and Mesh Topology (RT-MT) gave a throughput of 900Mbps, as against 300Mbps and 500Mbps obtained for ring and mesh topology, respectively. The energy efficiency obtained for the hybrid RT-MT topology was 90Mbps/W as against 30Mbps/W and 50Mbps/W recorded for Ring and Star topologies, respectively. Similarly, a latency of 0.5ms was obtained using hybrid RT-MT, while the corresponding values obtained for ring and mesh topologies were 5ms and 2ms, respectively. Furthermore, the hybrid RT-MT topology gave PDR of 0.70, while the corresponding PDR values obtained for the ring and mesh topology were 0.10 and 0.30, respectively.

The results highlight the RT-MT topology as a technically and economically superior alternative for 5G mmwave small cell backhauling. Its ability to deliver higher throughput, lower latency, and greater energy efficiency under varying LOS conditions positions it as a robust and scalable architecture for next-generation wireless networks.

System Throughput

Figure 2 demonstrates the relationship between throughput and Small cell Base Stations (SBSs). The result shows that the LOS probability plays an important role in the system's throughput. The value increases with 100% LOS probability for any SNR value. Nevertheless, the relationship between the LOS probability and the throughput is inverse; that is, for a lower probability of LOS, throughput decreases, making it easier for the obstacles to block or weaken the signal, thus stimulating poor performance from the network. As can be observed from the throughput behaviour in each of the LOS probabilities, the SNR is low, which means that even with the optimum LOS, the throughput is very poor.

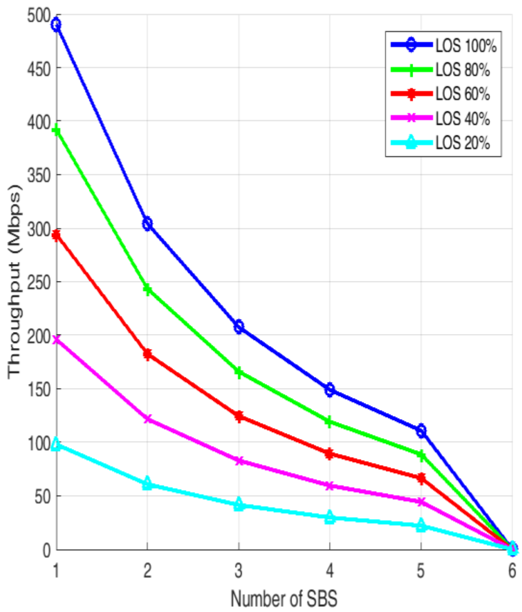

Figure 2. Relationship between throughput and Small Cell Base Stations (SBSs).

Energy Efficiency

Figure 3 demonstrates the relationship between the number of Small Base Stations (SBS) and energy efficiency under different Line-of-Sight (LOS) conditions. The analysis revealed that energy efficiency as well as throughput decreases with more SBS, suggesting that adding more SBS reduces the overall energy efficiency of the network. Higher LOS (100%) yields better energy efficiency, while lower LOS (20%) results in the lowest efficiency. The energy efficiency curves are higher when LOS is higher, indicating better performance in clearer conditions.

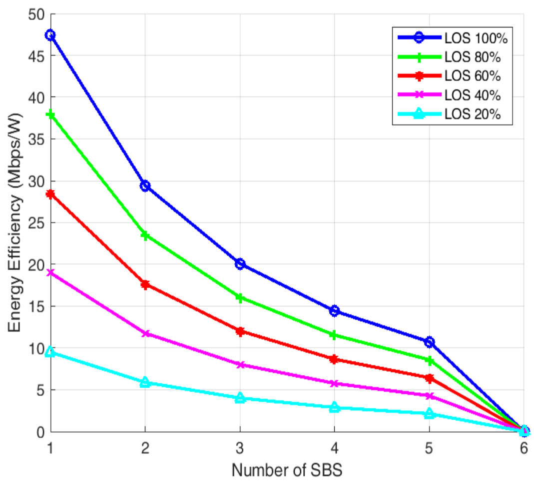

Figure 3: Relationship between Energy Efficiency and Number of Small Base Stations (SBS)

Figures 4 and 5 shows the relationship between latency and packet delay ratio (PDR) with respect to small cell Base Stations (SBS). However, figure 6 and figure 7 shows 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. Table 2 shows the comparative analysis result between ring, star and ring-mesh topology, that at 100% LOS, Hybrid Ring-Mesh 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 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 maximises energy efficiency while ensuring a stringent quality of service (QoS) and also offers considerable throughput and latency where there are a smaller number of small cell base stations.

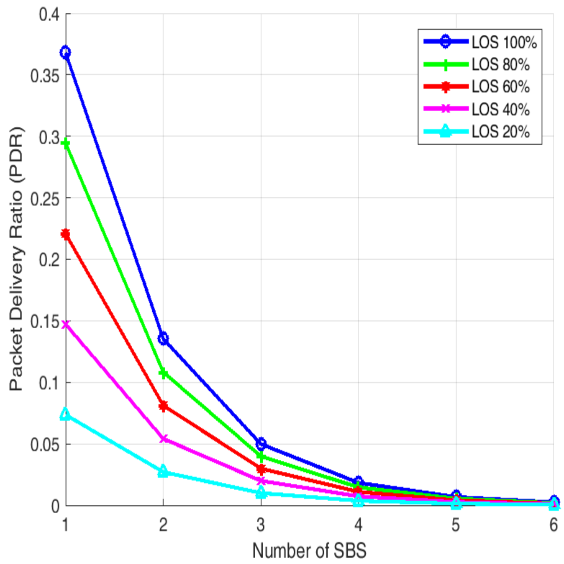

Figure 4: Relationship between Packet Delay Ratio (PDR) and Number of Small Base Stations (SBS)

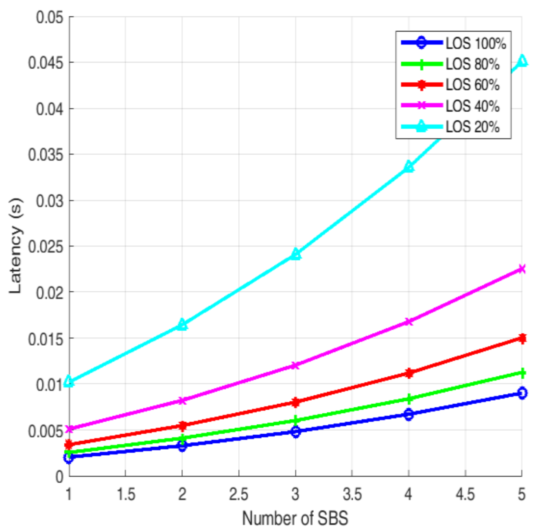

Figure 5: Relationship between Latency and Number of Small Base Stations (SBSs)

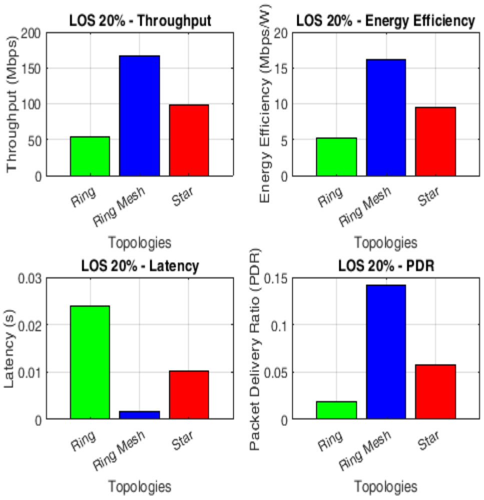

Figure 6: Comparison of Three Topologies using Parameters at 20% Line-of-Sight (LOS)

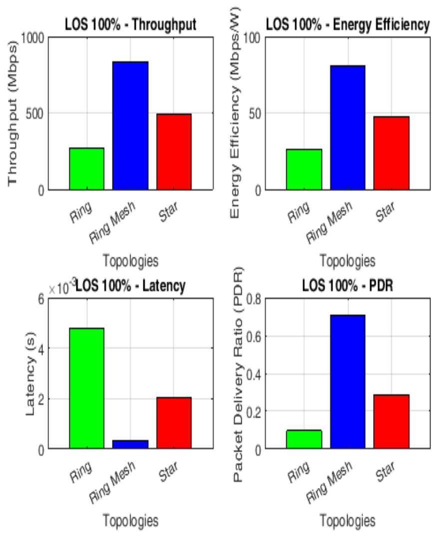

Figure 7: Comparison of Three Topologies using Parameters at 100% Line-of-Sight (LOS)

Table 2: Comparative Analysis

	Ring	**Star**	**Ring-Mesh**
Throughput	300 Mbps	500 Mpbs	900 Mbps
Latency	5 ms	2 ms	0.5 ms
Energy efficiency	30 Mpbs/W	50 Mpbs/W	90 Mpbs/W
Packet Delivery Ratio (pdr)	0.10	0.30	0.70

CONCLUSIONS

In conclusion, after executing simulations across the different backhaul topologies using aligned configuration settings, performance results that allow standardised 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.

The analysis revealed that energy efficiency decreases with more Small Cell Base Stations (SBSs), suggesting that adding more SBSs reduces the overall energy efficiency of the network. Future research work can be centered on improving energy efficiency for higher number of SBSs. More complex modulation techniques can also be considered in future work to determine how data is modulated and routed in the system.

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