Performance Evaluation of Hybrid Optical and Radio Relay Backhaul Solutions for Mobile Base Stations Using NCTUns Simulation

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Abstract: The rapid expansion of mobile communication networks requires reliable, high-capacity, and resilient backhaul solutions, particularly in regions with limited fiber infrastructure. This paper presents a comparative performance evaluation of radio relay links (RRL) and fiber-optic communication lines (FOCL) deployed at mobile base stations using the NCTUns Network Simulator (version 6.0). A virtualized simulation environment was developed to model realistic mobile backhaul scenarios, including traffic queues, routing behavior, wireless channel fading, and error characteristics. Key performance indicators such as bit error rate (BER), signal-to-noise ratio (SNR), data transmission rate, and end-to-end latency were evaluated under identical network conditions with constant bit rate traffic. Simulation results indicate that FOCL significantly outperforms RRL, achieving BER values on the order of 10^{-9}, stable SNR levels above 45 dB, data rates exceeding 100 Gbit/s, and average latency close to 1 ms. In contrast, RRL exhibits BER values around 10^{-5}, SNR levels between 20 and 25 dB, and latency ranging from 5 to 20 ms, while offering advantages in rapid deployment and infrastructure flexibility. Based on these results, a hybrid FOCL/RRL backhaul architecture with a logic-based backup selection algorithm is proposed. The algorithm enables automatic switching between fiber-optic and radio relay links based on latency and link quality thresholds, thereby improving network resilience, availability, and service continuity.

1 INTRODUCTION

The rapid development of mobile communication networks has significantly increased the demand for reliable, high-capacity, and low-latency backhaul solutions for mobile base stations. In modern telecommunication systems, backhaul performance directly affects network stability, service continuity, and user experience. Therefore, the selection of an appropriate transmission technology for connecting base stations to the core network has become an important engineering task [1], [2].

Among the most widely used backhaul technologies are radio relay links (RRL) and fiber-optic communication lines (FOCL). Radio relay communication enables relatively fast deployment and flexible network extension, especially in areas with limited communication infrastructure. However, its performance is sensitive to weather conditions, transmission distance, and electromagnetic interference. In contrast, fiber-optic communication provides high bandwidth, low bit error rate, stable signal quality, and minimal latency, although installation and maintenance costs are usually higher [3], [4].

Radio relay communication refers to wireless transmission based on electromagnetic waves and line-of-sight propagation. It is often used in decimeter and centimeter wavelength ranges, where directional antennas and long-distance transmission are feasible. In practical applications, radio relay systems are valuable when communication networks must be deployed quickly or when wired infrastructure is unavailable [5], [6]. At the same time, fiber-optic systems transmit information through light pulses and are known for their very high throughput, low attenuation, and immunity to electromagnetic interference. These properties make FOCL highly suitable for high-performance telecommunication networks [3], [7].

A hybrid backhaul architecture combining FOCL and RRL can improve the resilience of mobile communication systems by using fiber-optic links as the primary channel and radio relay links as a backup path. Such an approach is especially relevant in regions where fiber deployment is expensive, geographically complicated, or vulnerable to physical damage. Figure 1 illustrates the proposed hybrid fiber-optic and radio relay backhaul architecture connecting the central office and remote radio units.

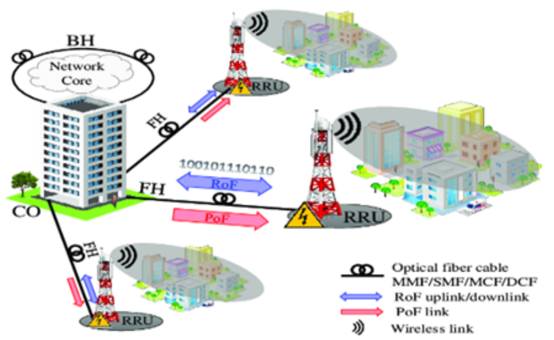

Figure 1: Architecture of the hybrid fiber-optic and radio relay backhaul system between the Central Office (CO) and Remote Radio Units (RRUs).

Despite the practical use of both technologies, there remains a need for a quantitative comparison of their performance under identical operating conditions using simulation-based analysis. In particular, the influence of the communication medium on bit error rate, signal-to-noise ratio, transmission speed, and latency requires clearer evaluation for mobile base station backhaul scenarios [2], [8].

Therefore, the aim of this study is to compare the performance of radio relay and fiber-optic backhaul solutions for mobile base stations using the NCTUns Network Simulator and to propose a logic-based backup selection algorithm for hybrid FOCL/RRL operation. The novelty of the study lies in the integrated simulation-based comparison of the two communication technologies under the same traffic conditions and in the development of an automatic failover decision logic for resilient mobile backhaul operation.

2 MATERIALS AND METHODS

The comparative performance evaluation of radio relay links and fiber-optic communication lines was carried out using the NCTUns Network Simulator version 6.0. A virtual simulation environment was created to reproduce a mobile backhaul network in which a base station communicates with the core network through both fiber-optic and radio relay channels. The simulator was selected because it allows realistic modeling of traffic behavior, routing processes, wireless fading effects, delay characteristics, and packet errors [9], [10].

The methodological basis of the study included analysis of relevant scientific publications, comparative modeling of communication channels, and numerical assessment of key quality indicators. The main performance parameters selected for the evaluation were bit error rate (BER), signal-to-noise ratio (SNR), transmission speed, and end-to-end latency. These indicators were chosen because they directly reflect communication quality, channel reliability, and network responsiveness in mobile backhaul systems [1], [4], [10].

The simulation topology consisted of a core network node connected to a mobile base station through two parallel backhaul paths. The communication distance between nodes was configured as 5 km. For the FOCL scenario, the transmission rate was set to 100 Gbit/s, the propagation delay to 1 ms, and the channel type to a wired error-free model. For the RRL scenario, the carrier frequency was set to 18 GHz, the bandwidth to 40 MHz, the transmission rate to 10 Gbit/s, and the wireless medium to a fading channel model in order to reproduce realistic radio channel conditions [3], [8], [9].

Traffic generation in the simulation was configured using a Constant Bit Rate (CBR) source with a packet size of 1024 bytes and a traffic rate of 50 Gbit/s. The duration of each simulation experiment was 300 seconds; each scenario should be run multiple times with averaged results to ensure statistical reliability, and the exact number of repetitions used should be explicitly reported. Both backhaul technologies were tested under identical traffic conditions to ensure the comparability of the obtained results. In addition, radio relay links were assessed under different weather and distance conditions to analyze their sensitivity to environmental factors [4], [5].

The NCTUns environment was also used to configure simulation preferences, terminal interaction, queue-based traffic behavior, and parameter monitoring. The simulator makes it possible to analyze packet flow, packet loss, delay characteristics, and the performance of network elements within a unified environment [9], [10]. Figures 2-7 present the main structural and configuration elements used in the simulation model.

To provide a practical applied IT contribution, a hybrid FOCL/RRL backup selection algorithm was defined based on real-time backhaul performance indicators obtained from the NCTUns simulation environment. The decision-making logic uses the operational state of the fiber-optic link together with threshold values for BER, SNR, and latency. The threshold values were defined as follows: BER_threshold = 10^{-6}, SNR_threshold = 25 dB, and Latency_threshold = 5 ms. If the fiber-optic link fails or its quality deteriorates below the acceptable threshold, the radio relay link is activated as a backup path. When the FOCL parameters recover, the system switches traffic back to the primary fiber-optic path [5], [6], [10].

Figure 2: Architecture of a Radio Relay Communication System.

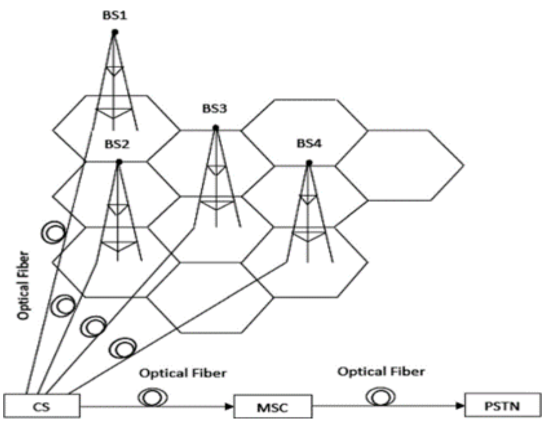

Figure 3: Backhaul connection of a cellular network using optical fiber.

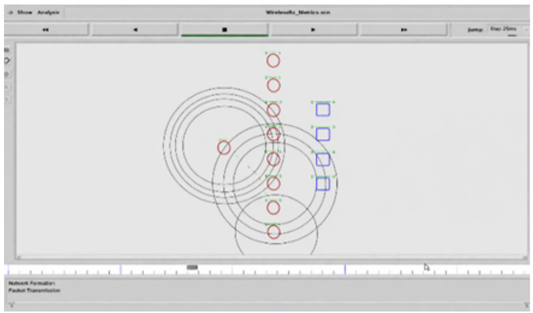

Figure 4: Wireless relay network simulation in NCTUns.

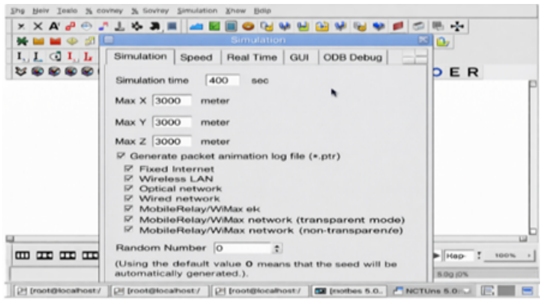

Figure 5: NCTUns network simulator preference configuration window.

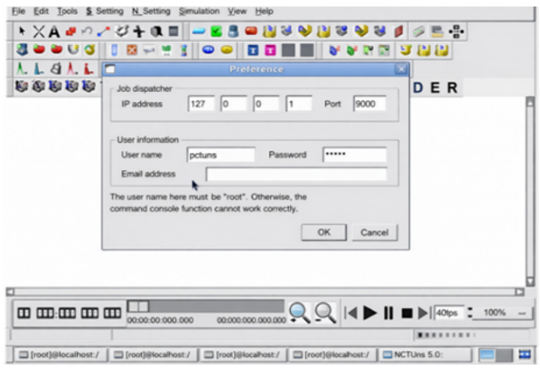

Figure 6: NCTUns simulation parameter configuration window.

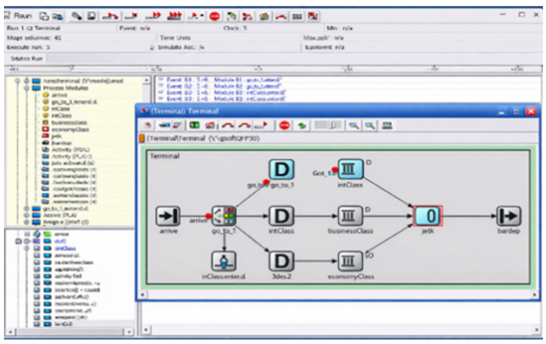

Figure 7: Queue-based traffic modeling in a terminal system using NCTUns.

The decision logic can be summarized as follows:
Input parameters:

- BER_FOCL. Bit error rate of the fiber-optic link.
- SNR_FOCL. Signal-to-noise ratio of the fiber-optic link.
- LinkStatus_FOCL. Operational status of the fiber link.

Decision logic:

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IF (LinkStatus_FOCL = DOWN) OR (BER_FOCL > BER_threshold) OR (SNR_FOCL < SNR_threshold)
THEN
    Activate radio relay link (RRL) as backup backhaul
ELSE
    Maintain fiber-optic link (FOCL) as primary backhaul
ENDIF

IF (FOCL restored) AND (BER_FOCL ≤ BER_threshold) AND (SNR_FOCL ≥ SNR_threshold)
THEN
    Switch traffic back to FOCL
ENDIF
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This algorithm can be integrated into the network management plane using continuous monitoring and OAM alarms, thereby improving service continuity and automatic failover capability in hybrid communication systems [5], [10].

3 RESULTS

The simulation results demonstrated a clear performance advantage of fiber-optic communication over radio relay communication in all evaluated metrics. Table 1 summarizes the comparative results obtained for both backhaul technologies under identical simulation conditions. Fiber-optic communication achieved an average BER of 10^{-9}, an SNR of about 50 dB, a transmission rate of 100 Gbit/s, and an average latency of 1 ms. By contrast, radio relay communication showed an average BER of 10^{-5}, an SNR in the range of 20-25 dB, a transmission rate of 10 Gbit/s, and latency ranging from 5 to 20 ms.

The obtained data indicate that FOCL provides significantly better transmission quality and lower delay than RRL in mobile backhaul operation. In particular, the BER of the fiber-optic link remained almost negligible throughout the simulation, whereas the radio relay link produced noticeably higher error rates because of the fading wireless channel and lower signal stability [3], [7], [10].

The radio relay link was additionally analyzed under different weather and distance conditions. The results presented in Table 2 show that RRL performance strongly depends on external factors. Under good weather and short-distance conditions, SNR remained relatively high and BER remained low. However, under rain or snow and at longer distances, SNR decreased significantly while BER increased, indicating reduced communication reliability [4], [5].

Figure 8 illustrates the variation of BER and SNR values in the radio relay communication system under different operational conditions. The figure confirms that weather deterioration and increased transmission distance directly reduce signal quality and increase the probability of transmission errors [4], [10].

Table 1: Comparison of radio-relay and fiber-optic communication systems.

System Type	BER (Average)	SNR (Average, dB)	Speed (Gbit/s)	Delay / Latency (ms)
Radio-Relay (RRL)	10^{-5}	20-25	10	5-20
Fiber-Optic Communication (FOCL)	10^{-9}	50	100	1

Table 2: Variation of SNR and BER in a radio-relay communication system under different conditions.

Condition / Distance	SNR (dB)	BER	Note
Good weather, short distance	High (20-30)	Very low (below 10^{-6})	Strong signal, minimal errors
Rain / snow, short distance	Medium (10-20)	Low to medium (10^{-5} - 10^{-4})	Noise increases, errors slightly higher
Good weather, long distance	Medium (10-15)	Medium (10^{-4} - 10^{-3})	Signal strength decreases over long distances
Rain / snow, long distance	Low (5-10)	High (above 10^{-3})	Weather effect is strong, BER increases

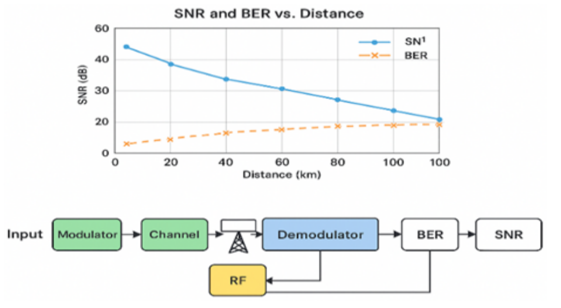

Figure 8: Variation of SNR and BER in a radio-relay communication system.

Figures 9-12 present a direct visual comparison of the main performance indicators of FOCL and RRL. Figure 9 shows that fiber-optic communication provides higher and more stable SNR values than radio relay communication. Figure 10 demonstrates that FOCL has a significantly lower BER than RRL. Figure 11 confirms the much higher transmission speed of the fiber-optic link, while Figure 12 shows that delay in FOCL remains minimal compared with radio relay communication [3], [7], [8], [10].

Figure 9 illustrates the comparison of SNR performance between fiber-optic and radio relay systems. Fiber-optic communication demonstrates higher and more stable SNR values.

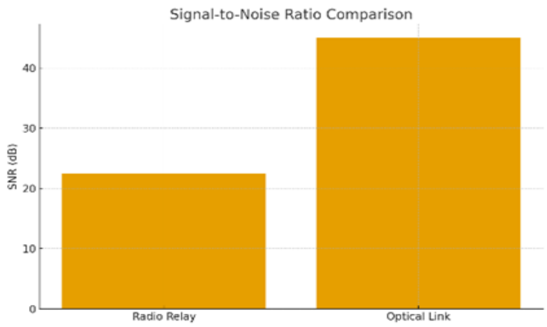

Figure 9: Comparative Analysis of Signal-to-Noise Ratio (SNR).

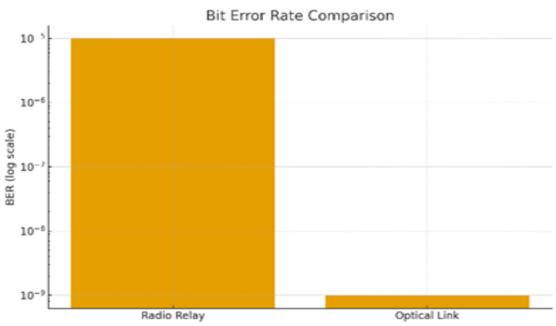

Figure 10: Comparative Analysis of Bit Error Rate (BER).

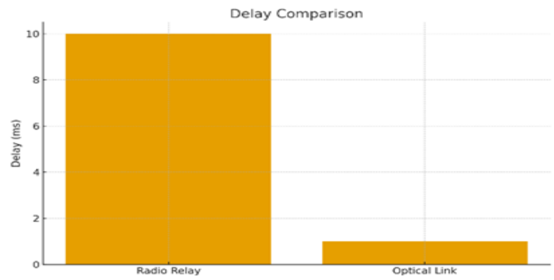

Figure 11: Comparative Analysis of Data Transmission Rate

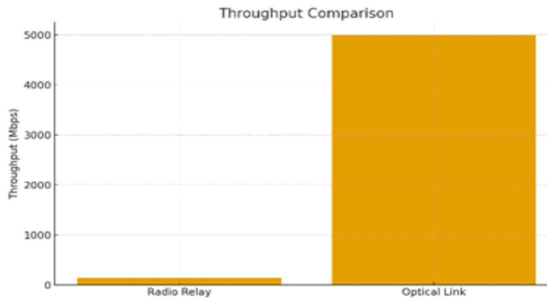

Figure 12: Comparative Analysis of Delay Metrics

Overall, the results confirm that optical communication outperforms radio relay communication in BER, SNR, transmission speed, and latency. At the same time, the simulation also shows that radio relay links remain operationally useful in situations where fast deployment and infrastructure flexibility are required [4], [5].

4 DISCUSSION

The obtained results indicate that fiber-optic communication is the more efficient solution for high-capacity and low-latency mobile backhaul networks. Its superior performance in BER, SNR, and delay can be explained by the physical properties of optical transmission, including low attenuation, immunity to electromagnetic interference, and the ability to support very high channel capacity. These features make FOCL especially suitable for modern communication systems requiring stable and continuous high-speed data exchange [3], [7].

In contrast, radio relay communication demonstrated lower transmission quality primarily because wireless propagation is more vulnerable to fading, atmospheric effects, and distance-related losses. This explains the observed rise in BER and the decrease in SNR under rain, snow, and long-distance conditions. Although the radio relay link has lower capacity and higher latency than FOCL, it retains considerable practical value because of its relatively fast installation, mobility, and reduced dependence on cable infrastructure. This is particularly important in remote regions, emergency deployment situations, or environments where laying fiber is technically difficult or economically inefficient [4]-[6].

An important outcome of the study is the proposed hybrid FOCL/RRL architecture with a threshold-based backup selection algorithm. The simulation confirms that combining a high-performance fiber-optic primary path with a radio relay backup path can improve service continuity and communication resilience. In practical network deployments, such an approach may reduce the risk of service interruption caused by fiber damage, infrastructure failure, or local performance degradation. The proposed decision logic is simple enough for practical implementation in the network management plane and can support automatic failover based on continuously monitored communication quality indicators [5], [6], [10].

In addition, recent studies on data-driven modeling and feature-based decision mechanisms confirm that intelligent analytical approaches can improve adaptive selection processes in complex digital systems [11].

At the same time, the present study has several limitations. First, the conclusions are based on simulation results and were not validated in a real field environment. Second, the analysis considered a fixed network topology and predefined traffic parameters, which may not fully represent all practical deployment scenarios. Third, the study focused on technical performance and did not include a detailed economic assessment of deployment and maintenance costs. Future research should therefore include field experiments, adaptive threshold optimization for backup switching, and techno-economic analysis of hybrid backhaul configurations [8], [10].

5 CONCLUSIONS

This study presented a comparative performance evaluation of radio relay and fiber-optic backhaul solutions for mobile base stations using the NCTUns Network Simulator. The results showed that fiber-optic communication provides substantially better performance in terms of bit error rate, signal-to-noise ratio, transmission speed, and latency. These characteristics make FOCL the preferred solution for high-performance, future-oriented mobile communication networks [3], [7], [10].

At the same time, radio relay communication remains a practical and valuable complementary technology because of its deployment flexibility, rapid installation, and lower dependence on wired infrastructure. Although its performance is more sensitive to weather and transmission distance, it can effectively serve as a backup communication channel when the primary fiber-optic link becomes unavailable or degraded [4], [5], [6].

In addition, the proposed hybrid FOCL/RRL architecture with a logic-based backup selection algorithm represents a practical applied IT contribution for resilient mobile backhaul systems. By enabling automatic switching between primary and backup communication channels based on real-time performance indicators, the algorithm improves network reliability, availability, and service continuity. Future work should focus on field validation of the simulation results and on the development of cost-aware adaptive hybrid backhaul strategies [5], [10].

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