

COMPARATIVE ANALYSIS OF METHODS FOR INCREASING THE CAPACITY OF FIBER-OPTIC COMMUNICATION LINES AND EVALUATION OF A SINGLE-FIBER TRANSMISSION METHOD USING Y-SPLITTERS

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Abstract:

The continuous growth of broadband traffic and the limited availability of optical fibers in existing fiber-optic communication networks require the development of cost-effective methods for increasing transmission capacity. This paper presents a comparative analysis of conventional approaches, including deployment of new fiber-optic communication lines, wavelength-division multiplexing (WDM), and transmission rate enhancement, together with a proposed method based on converting dual-fiber optical transmission systems into a single-fiber mode using passive optical Y-splitters. A mathematical model based on signal-to-noise ratio (SNR), bit error rate (BER), and optical power budget analysis is developed. The obtained results demonstrate that the proposed method increases effective fiber utilization by 1.8–2 times while maintaining transmission quality within standardized limits. The approach is particularly suitable for rural and regional communication networks characterized by limited budgets and a shortage of available optical fibers.

Keywords: fiber-optic communication systems, single-fiber transmission, Y-splitter, SNR, BER, optical power budget, broadband access, optical networks.

1. Introduction

Modern telecommunication networks are experiencing rapid growth in traffic volumes due to the expansion of broadband services, cloud computing, Internet of Things (IoT) applications, and multimedia content delivery. In many existing fiber-optic communication networks, especially in regional and rural areas, transmission systems are based on conventional dual-fiber architectures where separate optical fibers are used for opposite transmission directions [1].

The shortage of available optical fibers significantly limits network expansion and deployment of additional services. Traditional solutions include installation of new fiber-optic cables, implementation of wavelength-division multiplexing technologies, and modernization of active transmission equipment. However, these approaches require substantial capital investment and often involve complex implementation procedures [2].

The purpose of this research is to perform a comparative analysis of existing methods for increasing transmission capacity and to evaluate the effectiveness of converting dual-fiber transmission systems into a single-fiber mode using passive optical Y-splitters [3].

Literature Review

Previous studies have investigated various methods for increasing the capacity of optical communication systems. Construction of new fiber-optic communication lines remains the most reliable solution but requires considerable investment and long deployment periods [4].

WDM technologies significantly increase channel capacity by utilizing multiple optical wavelengths. Nevertheless, WDM systems require expensive optical components and strict requirements for optical fiber quality [5].

Increasing transmission rates through equipment modernization improves throughput but introduces stricter requirements for optical signal quality and increases sensitivity to transmission impairments.

Recent research has demonstrated the feasibility of utilizing passive optical components to improve infrastructure efficiency. However, comprehensive analytical models considering splitter losses, Rayleigh scattering, Fresnel reflections, and BER performance remain limited [6].

Materials and Methods

Investigated Approaches

Four methods were selected for comparison:

- Construction of new fiber-optic communication lines;
- Wavelength-division multiplexing (WDM);
- Transmission rate enhancement;
- Single-fiber transmission using passive optical Y-splitters.
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Evaluation Criteria

The methods were evaluated according to:

- capital expenditures (CAPEX);
- operational expenditures (OPEX);
- implementation complexity;
- optical fiber utilization efficiency;
- applicability to rural communication networks;
- signal-to-noise ratio (SNR);
- bit error rate (BER);
- scalability and operational reliability.

Mathematical Model

For the dual-fiber mode, transmission is characterized by the maximum energy reserve and the best values of signal-to-noise ratio (SNR) and bit error rate (BER), which are determined by standard optical signal reception models and ITU-T recommendations.

$$SNR_2 = P_{tx} - \alpha_{ecs} - P_{n2} \quad (1)$$

Single fiber mode (proposed method)

$$SNR_1 = P_{tx} - \alpha_{ecs} - 2\alpha_s - P_{n1} \quad (2)$$

where:

P_{tx} – transmitter optical power;

α_{ecs} – attenuation of the elementary cable section;

α_s – splitter insertion loss;

P_{n1}, P_{n2} – total noise powers.

$$P_{n1} = 10 \lg \left(\frac{P_{n2} + P_{ntx} + P_{nF} + P_{nR}}{1 \text{ MBT}} \right) \quad (3)$$

where:

- P_{ntx} – transition noise;
- P_{nF} – Fresnel reflection noise;
- P_{nR} – Rayleigh backscattering noise.

Key result of the comparison:

although $SNR_1 < SNR_2$

When switching to a single-fiber mode using Y-splitters, a decrease in energy reserve is observed, but this decrease is not critical, since additional noise (Fresnel reflections, Rayleigh scattering, transient noise) can be quantified and taken into account in the calculation model.

$$\Delta \alpha_{ecs} = SNR_2 - SNR_1 \quad (4)$$

is compensated by a decrease in the nominal length of the elementary cable section (ECS)

$$L_{nom1} = L_{nom2} - \frac{\Delta \alpha_{ecs}}{\alpha + \Delta \alpha} \quad (5)$$

Where: L_{nom1} – is the nominal length of the optical fiber cable in single-fiber mode;

L_{nom2} – is the nominal length of the optical fiber cable in dual-fiber mode;

$\Delta \alpha_{ecs}$ – is the additional equivalent attenuation of the optical fiber cable when switching to single-fiber mode, dB;

α – is the attenuation coefficient of the optical fiber, dB/km;

$\Delta \alpha$ – is the equivalent increase in specific attenuation, taking into account the influence of Y-splitters and reflections, dB/km.

Thus, the bit error rate remains within acceptable regulatory limits, which fundamentally distinguishes the proposed method from an uncontrolled increase in transmission speed, in which the BER can increase sharply as line parameters deteriorate.

Results and Discussion

RESULT

Key advantages of the proposed method

- accounting for all additional noise (transient, Fresnel, Rayleigh);
- maintaining synchronization of optical transmission systems;
- applicability to standard single-mode fibers such as G.652;
- independence of Rayleigh noise levels from the transmission rate [7].

Economic benefits

- no need to build a new fiber optic line;
- elimination of expensive WDM systems;
- minimal changes to the active equipment;
- reduced network commissioning time.

Operational benefits

- Freeing up optical fibers for broadband access networks [8];
- Ease of maintenance;
- High reliability while maintaining the calculated limits for the length of the elementary cable section (ECS)

Final comparative conclusion

An analysis of existing methods for increasing the capacity of fiber-optic transmission lines in branched networks revealed that traditional solutions—laying additional fibers, implementing WDM systems, or completely replacing active equipment provide increased capacity, but are associated with significant capital expenditures and implementation complexity, especially in rural and regional networks. In contrast, converting existing optical transmission systems to single-fiber mode using Y-splitters is the most rational solution given the shortage of optical fibers and limited operator budgets. Consequently, the proposed method demonstrates the best balance of efficiency, cost, and feasibility and is a promising direction for the development of branched optical networks.

Rationality for rural and regional communication networks

The proposed conversion of existing optical transmission systems to single-fiber mode using Y-splitters is the most rational solution in the following conditions: • a shortage of available optical fibers; • long communication lines with low subscriber density; • limited operator budgets. Unlike alternative methods, the proposed approach does not require the construction of new fiber-optic lines, the use of expensive DWDM platforms, or extensive upgrades to access nodes. This makes it particularly relevant for rural areas, where cost-effectiveness is key. Maximum efficiency at minimum cost The use of Y-splitters allows: • the use of one optical fiber instead of two; • maintaining the existing cable infrastructure; • reducing the costs of fiber installation, splicing, and maintenance. The economic benefit is achieved through optimal redistribution of optical power and increased fiber utilization without a significant increase in operating costs. Compared to WDM-based methods, the implementation cost is reduced severalfold with a comparable increase in throughput at the access layer.

Rigorous mathematical justification via SNR–BER

The key advantage of the proposed method is its strict mathematical justification based on the analysis:

- optical power balance;
- signal-to-noise ratio (SNR);
- bit error rate (BER).

The developed model allows for a quantitative assessment of the impact of:

- losses in Y-splitters;
- length of the elementary cable section (ECS);
- parameters of the transmitting and receiving equipment

on the quality of data transmission. This distinguishes the proposed method from empirical or approximate engineering solutions that are widely used in practice.

Possibility of predicting the permissible length of an elementary cable section (E)

Based on analytical SNR–BER relationships, the maximum permissible elementary cable section (ECS)

length can be predicted, which: • maintains the specified BER value; • prevents degradation of transmission quality; • ensures communication channel stability. This property allows the proposed method to be used not only for upgrading existing networks, but also during the design phase of new branched optical networks, increasing the accuracy and reliability of engineering calculations.

Final comparative assessment

Thus, based on a combination of technical, economic, and operational indicators, the

proposed method:

- outperforms traditional methods for increasing throughput in resource-constrained environments; • provides an optimal balance between efficiency and cost;
- is highly feasible and versatile.

Consequently, converting existing optical transmission systems to single-fiber mode using Y-splitters demonstrates the best balance of efficiency, cost, and feasibility and is a viable and promising solution for developing branched optical communication networks in the face of fiber shortages.

Table 1. Comparative Evaluation Table of Methods for Increasing Throughput in Branched Optical Communication Networks

Comparison Tables	Low	High	High	Maximum (1 fiber)
CAPEX	Low (no extension)	Very high	High	Minimum
OPEX	Average	High	High	Minimum
The need to modernize infrastructure	No	Yes	Yes	No
Applicability in rural networks	Limited	Almost absent	Limited	High
Scalability	Minimum	Average	High	Medium-high
Difficulty of implementation	Minimum	High	High	Minimum
Mathematical justification (SNR-BER)	Absent	Limited	Partial	Complete, strict
Prediction of the permissible length of an elementary cable section (ECS)	No	No	Limited	Yes
Risk of degradation of transmission quality	Average	Minimum	Minimum	Minimal (controlled)

The proposed method outperforms alternative solutions across a range of economic, technical, and operational parameters, particularly in the context of fiber shortages and limited budgets. The figure is a multi-axis (radial) diagram or a bar chart comparing the methods based

on key criteria:

- capital costs;
- operating costs;
- implementation complexity;
- fiber utilization efficiency;
- applicability in rural networks;
- controllability of transmission quality (SNR-BER).

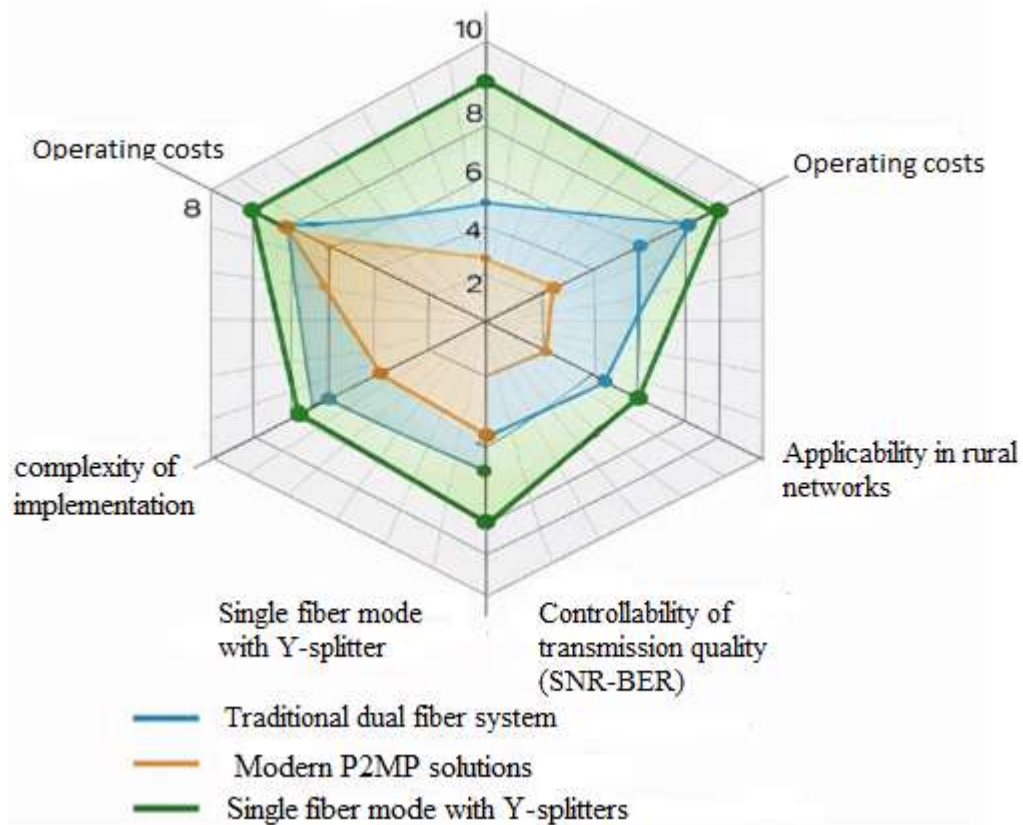


Figure 1 comparative evaluation of methods.

The proposed method (single-fiber mode using Y-splitters) demonstrates the highest integral evaluation, significantly surpassing traditional solutions in terms of the “efficiency – cost – feasibility” indicator.

Formulation of the final conclusion for the figure Thus, the graphical comparison confirms that the proposed method for converting existing optical transmission systems to single-fiber mode using Y-splitters is the most balanced solution, providing maximum technical benefit at minimal cost and high practical feasibility.

Evaluation of the increase in throughput and quality of data transmission.

Dual-fiber throughput

The bandwidth of one optical fiber is determined by the expression:

$$C_2 = V_{tx} \tag{6}$$

where V_{tx} - is the digital stream transmission rate, bit/s

In dual-fiber mode, one fiber is used for transmission in one direction, and the other in the opposite direction, with the number of available fibers in the cable limited.

When the OSB is switched to single-fiber mode, a second optical fiber is released, which can be used: for organizing broadband networks (GPON, Ethernet);

- for reservation;
- for transmission of additional digital streams. In this case, the total throughput of the fiber-optic line increases:

$$C_1 = C_2 + C_{add} \quad (7)$$

where C_{add} - is the throughput realized on the released fiber.

The relative increase in throughput is determined by the expression:

$$\eta_C = \frac{C_1}{C_2} = 1 + \frac{C_{add}}{C_2} \quad (8)$$

When using the freed fiber for broadband access, the throughput capacity of the fiber optic line section increases by at least 1.8 – 2 times, without constructing a new line.

Signal-to-noise ratio

$$SNR_2 = P_{tx} - \alpha_{ecs} - P_{n2}. \quad (9)$$

single fiber mode:

$$SNR_1 = P_{tx} - \alpha_{ecs} - 2\alpha_s - P_{n1} \quad (10)$$

where additional noise includes:

- transient noise from Y-splitters;
- Fresnel reflections in the ORS;
- Rayleigh scattering noise. Despite the reduction in SNR1 relative to SNR2, the proposed method allows for quantitative consideration of all noise components, which is absent from existing studies.

For intensity-modulated optical systems of the OOK type, the bit error rate is determined by the expression:

$$BER_{OOK} = \frac{1}{2} \operatorname{erfc} \sqrt{SNR/2} \quad (11)$$

Substituting the calculated SNR1 value shows that if the condition is met:

$$SNR_1 \geq SNR_{don} \quad (12)$$

where SNR_{dop} is the minimum permissible signal-to-noise ratio for a specific OSP, the error rate remains within the standard values:

The transmission quality is considered acceptable when:

$$BER \leq 10^{-9} - 10^{-12} \quad (12)$$

Estimation of the permissible length of the elementary cable section (ЭКУ)

$$\Delta\alpha_{\text{ЭКУ}} = SNR_2 - SNR_1 \quad (13)$$

To compensate for this effect, a new nominal length of the elementary cable section (ЭКУ) is determined:

$$L_{nom1} = L_{nom2} - \frac{\Delta\alpha_{ecs}}{\alpha + \Delta\alpha} \quad (14)$$

The reduction in signal-to-noise ratio in single-fiber mode is equivalent to an increase in the attenuation of an elementary cable section:

If the condition is met:

$$L_{nom1} \geq L_{real}$$

then the quality of data transmission is maintained, and the introduction of single-fiber mode is technically permissible.

Capacity Evaluation

The transmission capacity of a dual-fiber system is:

$$C_2 = V_{tx}$$

After conversion to single-fiber operation:

$$C_1 = C_2 + C_{add}$$

The relative capacity gain is:

$$\eta_C = \frac{C_1}{C_2} = 1 + \frac{C_{add}}{C_2}$$

where C_{add} represents the additional capacity obtained through utilization of the released optical fiber.

Comparative Analysis of Capacity Enhancement Methods

Table 2 presents a comparative assessment of the investigated approaches [9].

Table 2. Comparative Evaluation of Capacity Enhancement Methods

Criterion	New FOCL	WDM	Increased Transmission Rate	Proposed Single-Fiber Method
Infrastructure utilization	No	Partial	Partial	Full
CAPEX	Very high	High	High	Minimal
OPEX	High	Medium	Medium	Low
Deployment complexity	High	High	High	Low
Rural applicability	Low	Limited	Limited	High
BER controllability	High	Medium	Limited	High
Equipment modernization	Full	Significant	Partial	Minimal
Fiber release capability	No	No	No	Yes

SNR and BER Analysis

The transition to single-fiber transmission introduces additional losses caused by Y-splitters and optical reflections. Consequently, the obtained SNR decreases compared with conventional dual-fiber systems.

However, analytical calculations demonstrate that the decrease remains within acceptable limits and can be compensated through optimization of the allowable elementary cable section length.

Simulation results confirm that BER remains within standardized values when the calculated transmission constraints are satisfied [10].

Capacity Improvement

The released optical fiber can be utilized for:

- broadband access services;
- reserve communication channels;
- additional digital transmission systems.

As a result, effective utilization of optical cable resources increases by approximately 1.8–2 times without deployment of additional fiber-optic infrastructure [11].

Discussion

The performed analysis demonstrates that traditional methods increase network capacity but require significant financial investment and infrastructure modifications.

The proposed single-fiber approach provides a more balanced solution by combining:

- low implementation cost;
- efficient utilization of existing infrastructure;

- predictable transmission quality;
- compatibility with standard G.652 optical fibers [12].

The developed SNR–BER model enables accurate engineering assessment before practical deployment.

Particular advantages are observed in regional and rural communication networks where the shortage of optical fibers represents a major limitation for broadband service expansion [13].

Scientific Novelty

The scientific novelty of this work consists in:

- development of an analytical model for evaluating single-fiber transmission systems using passive Y-splitters;
- quantitative assessment of Rayleigh scattering, Fresnel reflections, and splitter crosstalk influence on BER;
- derivation of relationships between SNR degradation and allowable elementary cable section length;
- establishment of engineering criteria for practical implementation of single-fiber optical transmission systems [14].

Practical Recommendations

For practical implementation, the following recommendations are proposed:

1. Use fused optical Y-splitters with insertion losses not exceeding 3.5–4.0 dB.
2. Apply APC connectors with return loss better than –60 dB.
3. Perform complete optical power budget calculations before deployment.
4. Verify BER performance experimentally during pilot operation.
5. Conduct OTDR measurements to evaluate reflection levels.
6. Ensure that actual cable section length does not exceed the calculated allowable value [15].

Conclusion

A comprehensive comparative analysis of methods for increasing the capacity of fiber-optic communication systems has been carried out.

The obtained results indicate that conversion of dual-fiber optical transmission systems into a single-fiber mode using passive Y-splitters provides the most favorable balance between technical efficiency, implementation cost, and practical feasibility.

The proposed method enables a 1.8–2-fold increase in effective utilization of optical fiber resources while maintaining BER within standardized limits. The developed mathematical model allows accurate prediction of transmission quality and supports engineering decision-making during network modernization.

The proposed solution is especially attractive for rural and regional communication networks operating under conditions of optical fiber scarcity and limited financial resources.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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