MODELING THE TOPOLOGY OF FSON USING DIJKSTRA'S ALGORITHM

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Abstract

This paper focuses on modeling the topology of Free Space Optical Networks (FSON) using Dijkstra's algorithm, demonstrating its potential for efficient and reliable data transmission in distributed communication systems. The work highlights the integration of Li-Fi technology and graph theory to optimize routing and minimize time costs, ensuring adaptability and scalability for real-world applications. By addressinFg challenges like interference and line-of-sight constraints, the proposed methodology enhances network performance for smart cities, IoT systems, and space communications. The results confirm the effectiveness of the approach in improving bandwidth efficiency, reducing delays, and dynamically adapting to changing network conditions.

Keywords: Free Space Optical Networks, Dijkstra's Algorithm, Network Topology, Li-Fi Technology, Wireless Communication

I. Introduction

In the context of the rapid growth of data transmission volumes and the increasing number of connected devices, the demands on wireless communication technologies have risen significantly. Traditional radio frequency channels, despite their widespread use, face several limitations, including spectrum congestion, high energy consumption, and scalability challenges in dense urban environments. In response to these challenges, optical data transmission technologies, such as Li-Fi (Light Fidelity) and Free Space Optical Networks (FSON), have garnered particular interest [1-8].

Li-Fi utilizes visible light, ultraviolet, or infrared waves for data transmission, offering unique advantages such as high-speed communication, low latency, and reliability. This technology is actively being implemented in smart city systems, industrial automation, and even household devices. It is particularly useful for indoor data transmission, such as in offices and residential buildings, as well as for creating high-speed links between mobile devices.

On the other hand, FSON focuses on data transmission through open space using laser beams. These systems can provide high-speed connectivity over long distances, making them a promising solution for space communications, inter-building networks in densely populated metropolises, and satellite connectivity. A key advantage of FSON is its lack of dependence on physical infrastructure, which reduces costs and simplifies network deployment. However, these systems are sensitive to external factors, such as weather conditions and the need for line-of-sight communication.

Thus, Li-Fi and FSON technologies represent two complementary approaches to addressing modern communication challenges. Their use not only expands data transmission capabilities but also allows adaptation to various scenarios, including integration into existing systems, deployment in remote areas, and even applications in space.

Figure 1 illustrates the topology diagram developed based on graph theory. As shown in the figure, the FSON network establishes connections between the monitoring center, optical locator, low-Earth orbit satellites, aircraft, drones, and buildings within line-of-sight range. To ensure reliable communication among all system elements, various wavelengths are employed, minimizing interference and enhancing network capacity.

Specifically, the wavelengths used for communication between the optical locator and satellites are denoted as $\lambda_1, \lambda_2, \dots, \lambda_n, \lambda_d, \lambda_p$; between satellites as $\lambda'_1, \dots, \lambda'_n$; between satellites and buildings as $\lambda''_1, \dots, \lambda''_n$; between buildings as $\lambda^B_1, \dots, \lambda^B_n$; between the optical locator and buildings as $\lambda'''_1, \dots, \lambda'''_n$; and between the monitoring center and the optical locator as λ'_m. These wavelengths enable independent data transmission between nodes, improving the overall efficiency of the network.

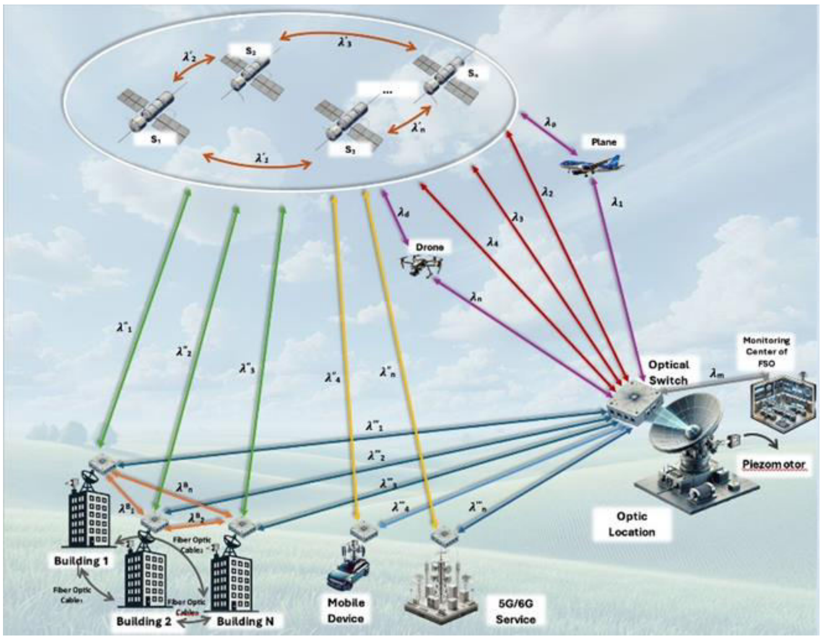

Figure 1: *Data Transmission Scheme in a Network Using Li-Fi and Satellites*

II. Network Topology and Routing Parameters

Modern data transmission systems impose stringent requirements on network topology and routing principles [1-6]. In distributed systems such as Free Space Optical Networks (FSON), efficient organization of communication between nodes is critically important. This chapter describes the network topology, based on graph theory, and the parameters that determine optimal data transmission routes.

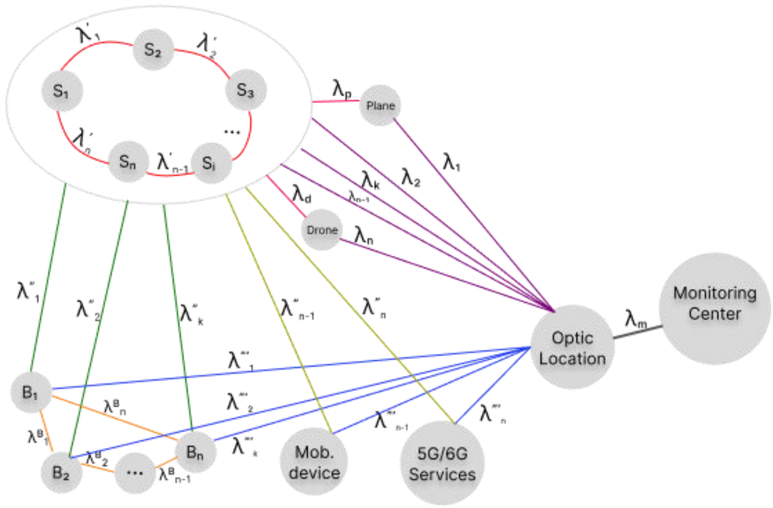

Figure 2: *FSON Network Topology with Nodes and Wavelengths*

Representing a network as a graph is one of the most effective ways to model complex interconnections [9]. In this topology, each node corresponds to an active network element, and the edges represent data transmission lines between the nodes. Fig. 2 illustrates a network structure in which communication is organized between:

• Buildings $(B_1, B_2, \dots, B_n)$,

• Low-Earth orbit satellites $(S_1, S_2, \dots, S_n)$,

• Mobile devices,

• Drones and aircraft,

• The monitoring center via an optical locator.

Each edge of the graph is characterized by the wavelength used for data transmission, minimizing interference between communication lines.

For instance:

• Wavelengths between satellites are denoted as $\lambda_1', \lambda_2', \dots, \lambda_n'$,

• Wavelengths between satellites and buildings as $\lambda_1'', \dots, \lambda_n''$,

• Wavelengths between a building and the locator as $\lambda_1''', \dots, \lambda_n'''$.

One of the primary constraints of such a network is the requirement for line-of-sight communication between nodes. This imposes limitations on node placement and interaction but enable s significantly higher data transmission speeds by using laser beams and minimizing signal loss.

The use of graph-based topology provides several key advantages:

• Flexibility: The ability to scale the network by adding new nodes without altering the existing structure,

• Efficiency: Minimization of data transmission delays through optimized routing,

• Reliability: The availability of alternative routes for data transmission reduces the risk of connection disruptions in case of individual node failures.

The system supports a high degree of adaptation to external conditions, such as weather changes, by utilizing alternative routes based on Dijkstra's algorithm (described in the next chapter).

To ensure efficient network operation, the following parameters are used to define data transmission routes between nodes:

• $\mathrm{d_i}$: The distance between node i and $i + 1$, which directly impacts the data transmission speed,

• $\mathrm{S_i}$: The data transmission speed for a given network segment (e.g., via Li-Fi),

• δ_i: The data processing delay at node i, depending on the type of equipment and the number of operations at the node.

To calculate the total data transmission time, the following formula is used:

$$T_{total} = \sum_{i=1}^{n}\left(\frac{d_i}{S_i} + \delta_i\right) \tag{1}$$

Where T_total – total time required for data transmission between two nodes. This formula accounts for all route parameters, enabling precise calculation of the time required for data transmission.

Impact of Parameters:

• Distance (d_i): The larger the distance between nodes, the greater the time required. Therefore, minimizing route length is one of the optimization goals,

• Data Transmission Speed (S_i): Depends on the technology used in the network (e.g., Li-Fi, laser communication lines). High-speed technologies significantly reduce T_{total},

• Delays (δ_i): Includes signal processing time at the node. Minimizing delays is achieved through optimization of hardware and software.

To describe the network, a weight matrix is used (Table 1), where each node is connected to others with corresponding parameters (distance, data transmission speed, delays). This matrix allows for efficient modeling of temporal costs between nodes:

• Values along the diagonal are zero, as a node has no cost to communicate with itself

•Represent the temporal costs of data transmission between nodes ($\lambda_1, \lambda_2, \dots, \lambda_n$) through the respective communication channels.

Table 1: *Weight Matrix Example*

From/To	Building 1	Building 2	…	Mobile device (Building n-1)	Cell tower (Building n)	Satellite 1	Satellite 2	…	Satellite n	Optic locator	Drone	Aircraft	Monitoring center
Building 1	0	λ^{b1}	∞	∞	$\lambda^{b}{}_{n}$	λ''^{1}	∞	∞	∞	λ'''^{1}	∞	∞	∞
Building 2	λ^{b1}	0	λ^{b2}	∞	∞	∞	λ''^{2}	∞	∞	λ'''^{2}	∞	∞	∞
…	∞	λ^{b2}	0	…	∞	∞	∞	…	∞	∞	∞	∞	∞
Mobile device (Building n-1)	∞	∞	…	0	$\lambda^{b}{}_{n}{}^{-1}$	∞	∞	∞	$\lambda''_{n}{}^{-1}$	$\lambda'''_{n}{}^{-1}$	∞	∞	∞
Cell tower (Building n)	$\lambda^{b}{}_{n}$	∞	∞	$\lambda^{b}{}_{n}{}^{-1}$	0	∞	∞	∞	λ''_{n}	λ'''_{n}	∞	∞	∞
Satellite 1	λ''^{1}	∞	∞	∞	∞	0	λ'^{1}	∞	λ'_{n}	$(\lambda^{1} + \lambda_{p})$	∞	λ_{p}	∞
Satellite 2	∞	λ''^{2}	∞	∞	∞	λ'^{1}	0	λ'^{2}	∞	λ^{2}	∞	∞	∞
…	∞	∞	…	∞	∞	∞	λ'^{2}	0	…	∞	∞	∞	∞
Satellite n	∞	∞	∞	$\lambda''_{n}{}^{-1}$	λ''_{n}	λ'_{n}	∞	…	0	$(\lambda_{n} + \lambda_{d})$	λ_{n}	∞	∞
Optic locator	λ'''^{1}	λ'''^{2}	∞	$\lambda'''_{n}{}^{-1}$	λ'''_{n}	$(\lambda^{1} + \lambda_{p})$	λ^{2}	∞	$(\lambda_{n} + \lambda_{d})$	0	λ_{n}	λ^{1}	λ_{m}
Drone	∞	∞	∞	∞	∞	∞	∞	∞	λ_{d}	λ_{n}	0	λ_{a}	∞
Aircraft	∞	∞	∞	∞	∞	λ_{p}	∞	∞	∞	λ^{1}	λ_{a}	0	∞
Monitoring center	∞	∞	∞	∞	∞	∞	∞	∞	∞	λ_{m}	∞	∞	0

III. Route Optimization and Results Analysis

Efficient data transmission in distributed communication systems is impossible without route optimization. Using Dijkstra's algorithm and the time parameters described in the previous chapter, the fastest and most stable paths between network nodes can be identified. This chapter describes the process of route optimization based on input data, the application of Dijkstra's method, and the analysis of results.

The input data for routing is based on a weight matrix reflecting the time costs of data transmission between nodes. The weight matrix considers:

• *Direct Line-of-Sight Communication:* Communication is possible only if a direct line of sight exists between nodes, a critical constraint in FSON networks.

• *Time Costs:* For each pair of nodes, time costs are calculated based on distance (d_i), transmission speed (S_i) and processing delay (δ_i). If direct communication between nodes is not possible, the cost is set to ∞.

• *Communication Channel Characteristics:* Different wavelengths ($\lambda_1, \lambda_2, \dots, \lambda_n$), are used to minimize interference and improve efficiency.

Example Weight Matrix: Table 1 demonstrates the temporal costs between nodes, where each element represents the cost of transmitting data between the respective nodes.

Dijkstra's Algorithm for Path Optimization — is a classical method for finding the shortest path in graphs. In the context of this system, the algorithm identifies routes with the minimal time cost. The main steps are as follows:

1.Initialization:

• All nodes are assigned initial cost values (∞), except for the starting node (0).

• A list of unprocessed nodes is created.

2.Node Selection with Minimal Cost:

• From the list of unprocessed nodes, the node with the lowest cost is selected.

3.Updating Neighboring Nodes:

• For each neighboring node, the cost is recalculated based on the current node.

• If the new route offers a lower cost than previously calculated, the values are updated.

4.Repeat:

• Steps 2 and 3 are repeated until all nodes are processed.

5.Route Formation:

•After completing the algorithm, the optimal path from the starting node to each other node is determined.

Table 2: *Final Table of Minimal Weights Between Network Nodes*

From/To	Building 1	Building 2	…	Mobile device Building n-1	Cell tower Building n	Satellite 1	Satellite 2	…	Satellite n	Optic locator	Drone	Aircraft	Monitoring center
Building 1		$x_{1(2)}$	…	$x_{1(n-1)}$	$x_{1(n)}$	$x_{1(n+1)}$	$x_{1(n+2)}$	…	$x_{1(2n)}$	$x_{1(k)}$	$x_{1(d)}$	$x_{1(p)}$	$x_{1(m)}$
Building 2	$x_{2(1)}$		…	$x_{2(n-1)}$	$x_{2(n)}$	$x_{2(n+1)}$	$x_{2(n+2)}$	…	$x_{2(2n)}$	$x_{2(k)}$	$x_{2(d)}$	$x_{2(p)}$	$x_{2(m)}$
…	…	…	…	…	…	…	…	…	…	…	…	…	…
Mobile device (Building n-	$x_{n-1(1)}$	$x_{n-1(2)}$	…		$x_{n-1(n)}$	$x_{n-1(n+1)}$	$x_{n-1(n+2)}$	…	$x_{n-1(2n)}$	$x_{n-1(k)}$	$x_{n-1(d)}$	$x_{n-1(p)}$	$x_{n-1(m)}$

1)													
Cell tower (Building n)	$x_{n(1)}$	$x_{n(2)}$	...	$x_{n(n-1)}$		$x_{n(n+1)}$	$x_{n(n+2)}$	...	$x_{n(2n)}$	$x_{n(k)}$	$x_{n(d)}$	$x_{n(p)}$	$x_{n(m)}$
Satellite 1	$x_{n+1(1)}$	$x_{n+1(2)}$	...	$x_{n+1(n-1)}$	$x_{n+1(n)}$		$x_{n+1(n+2)}$	...	$x_{n+1(2n)}$	$x_{n+1(k)}$	$x_{n+1(d)}$	$x_{n+1(p)}$	$x_{n+1(m)}$
Satellite 2	$x_{n+2(1)}$	$x_{n+2(2)}$	...	$x_{n+2(n-1)}$	$x_{n+2(n)}$	$x_{n+2(n+1)}$		...	$x_{n+2(2n)}$	$x_{n+2(k)}$	$x_{n+2(d)}$	$x_{n+2(p)}$	$x_{n+2(m)}$
...	...	...	...	...	...	...	...	...	...	...	...	...	...
Satellite n	$x_{2n(1)}$	$x_{2n(2)}$	...	$x_{2n(n-1)}$	$x_{2n(n)}$	$x_{2n(n+1)}$	$x_{2n(n+2)}$	...		$x_{2n(k)}$	$x_{2n(d)}$	$x_{2n(p)}$	$x_{2n(m)}$
Optic locator	$x_{k(1)}$	$x_{k(2)}$	...	$x_{k(n-1)}$	$x_{k(n)}$	$x_{k(n+1)}$	$x_{k(n+2)}$	...	$x_{k(2n)}$		$x_{k(d)}$	$x_{k(p)}$	$x_{k(m)}$
Drone	$x_{d(1)}$	$x_{d(2)}$	...	$x_{d(n-1)}$	$x_{d(n)}$	$x_{d(n+1)}$	$x_{d(n+2)}$	...	$x_{d(2n)}$	$x_{d(k)}$		$x_{d(p)}$	$x_{d(m)}$
Aircraft	$x_{p(1)}$	$x_{p(2)}$	...	$x_{p(n-1)}$	$x_{p(n)}$	$x_{p(n+1)}$	$x_{p(n+2)}$	...	$x_{p(2n)}$	$x_{p(k)}$	$x_{p(d)}$		$x_{p(m)}$
Monitoring center	$x_{m(1)}$	$x_{m(2)}$	...	$x_{m(n-1)}$	$x_{m(n)}$	$x_{m(n+1)}$	$x_{m(n+2)}$	...	$x_{m(2n)}$	$x_{m(k)}$	$x_{m(d)}$	$x_{m(p)}$	

The execution of Dijkstra's algorithm produces a routing table that provides the minimal time costs for each pair of nodes. Table 2 highlights the following:

• Displays the most efficient paths and their associated transmission times.

• Identifies key nodes with the most efficient connections, indicating their central role in the network.

• Highlights nodes where optimization is required, such as improving transmission speeds or reducing delays.

Advantages of Using Dijkstra's Algorithm:

1. Dynamic Routing: Routes are updated in real time based on current network conditions, ensuring adaptability to environmental factors or system changes.

2. Efficient Resource Utilization: The algorithm selects routes with minimal costs, maximizing the network's overall throughput.

3. Minimized Delays: By optimizing time costs, the network ensures fast and stable data transmission.

4. Scalability: The system easily adapts to the addition of new nodes or connections without losing its effectiveness.

IV. Conclusion

Data transmission route optimization is a fundamental element for the efficient operation of distributed networks. The system considered, based on Dijkstra's algorithm and Li-Fi technologies, demonstrates a high level of adaptability, reliability, and performance.

The primary advantages of such a network lie in the efficient utilization of resources by organizing communication between nodes with direct line-of-sight, minimizing signal loss, and increasing data transmission speeds. The use of multiple wavelengths significantly reduces interference and enhances bandwidth, making the network scalable and flexible for adding new nodes without requiring a complete infrastructure overhaul.

Dijkstra's algorithm enables dynamic routing by finding the shortest paths with minimal time costs, which is crucial for systems requiring high-speed and reliable data transmission. Analysis results confirm that nodes with minimal time costs become key points in the network, serving as primary data hubs, while high-cost segments highlight areas needing further optimization, such as upgrading hardware or increasing transmission speeds.

This system offers broad application prospects, including smart cities, space communications, Internet of Things (IoT) systems, and critical emergency or traffic management systems. An important area for future development is the integration with other communication technologies, consideration of external factors such as weather conditions, and the creation of automated routing systems capable of adapting to network changes in real time.

In conclusion, optimizing routes in distributed systems using Li-Fi technologies and Dijkstra's algorithm allows for the creation of a flexible, reliable, and efficient network. This network can tackle complex challenges and ensure stable data transmission even under constraints and dynamic conditions.

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