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Editorial

Optical Technologies Supporting 5G/6G Mobile Networks

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1. Introduction

Intensively developed mobile systems and networks 5G [1,2] and the planned 6G [3–6] constitute one of the most important elements of modern telecommunications. The technologies of 5G/6G mobile systems and networks have become so demanding that they cannot be constructed and implemented without advanced optical and photonic technologies. Core networks (CN), backhaul (BH), midhaul (MH), fronthaul (FH) [7] are the components that together constitute the networking realm of supporting 5G/6G mobile communications. Each of these components can be viewed as a service of an integrated X-haul/Crosshaul network [8,9], which can operate in a hybrid configuration based on Dense Wavelength Division Multiplexing (DWDM); Coarse Wavelength Division Multiplexing (CWDM); and optical transport network (OTN), Elastic Optical Network (EON), or passive optical network (PON) technologies [10–14]. Moreover, 6G mobile networks will use not only optical fiber networks but also Light Fidelity (Li-Fi) optical wireless connectivity [15–17]. The increasing density of base stations operating at higher and higher radio frequencies will necessitate the introduction of Li-Fi, which will be dictated by the popularization of IoT services [18,19] and the evolution of Industry 4.0 towards Industry 5.0. As the Radio Access Network (RAN) [20] domain of 5G/6G systems evolves towards Open Radio Access Networks (O-RANs) [21,22], heterogeneous, multi-domain, and multi-operator optical networks will have to work coherently to ensure the efficient transport of highly diverse network traffic, as well as the extensive use of the computing and data-collecting cloud [23]. In many situations, only synchronous networks with all-optical links and very efficient management of optical resources will be able to meet these challenges. The search for optical and photonic solutions useful in 5G/6G networks concerns not only transmission systems but also systems supporting the operation of effective antenna array systems, which in the O-RAN architecture are most often connected in the Massive Multiple-Input Multiple-Output (mMIMO) or Fiber-to-the-Antenna (FTTA) configurations [24,25]. In order to manage the shape of the radio beam, Fiber Bragg Grating (FBG)-based systems [26], optical delay lines, and multi-core fiber optics [27,28] are used. Optical networks and systems are now widely available, but the optimal use of their capabilities and resources in terms of transmission and energy consumption leaves much to be desired. In order to dynamically manage these resources, it is necessary to introduce machine learning techniques and elements of artificial intelligence [29]. It can be assumed that the intelligence of future universal optical networks will optimize and automate the planning of mobile networks and radio access.

This Special Issue contains five contributions that primarily concern research in the area of optics and photonics used in telecommunications systems, without which 5G mobile systems cannot currently exist and 6G wireless radio and optical systems cannot be implemented in the future. In particular, two articles focus on passive optical networks, one on advanced optical modulations, one on optical path analysis in multi-layer optical networks, and one on solutions for efficient software/settings management during the monitoring of large numbers of optical converters. A more detailed description of these contributions is provided below.

2. An Overview of Published Articles

Heterogeneous optical networks pose an increasing challenge. It seems that the standardization of systems forces the use of specific solutions to ensure that networks can be efficiently connected, effectively managed, and monitored together. However, in reality, the delivered systems are often equipped with proprietary solutions designed to enhance performance. As a result, connecting network components from different manufacturers becomes a big challenge, especially at the level of adapting the software that ensures the establishment of SDN connections, taking into account the required quality parameters. The Next-Generation RAN (NG-RAN) of 5G mobile systems uses network slicing services, which involve network traffic in various network domains. This is one of many examples where an optical transport network may be an assembly of many heterogeneous components that must work together. The first paper, authored by Wnęk et al. and titled "Data Processing and Distribution System Based on Apache NiFi" [30], presents an exemplary system based on Apache NiFi for collecting and processing data from transceivers as optical terminations of transmission links (log/setup files), taking into account their current settings adapted to the network requirements of the selected 5G system domain (5GC and NG-RAN). It was assumed that the monitoring data may concern even thousands of optical transceivers. The proposed use of Apache NiFi software to manage data from optical converters from various operator domains in the domain of 5G/6G mobile systems is a novel solution previously unavailable in both the research and commercial fields. In order to increase the efficiency of NiFi use, the standard software configuration was modified. The experiments were performed for configurations from 1 to 5 nodes in the NiFi cluster. This demonstrated the functioning of the proposed solution and the specific use of computing resources in the time needed to perform the task in the standard and optimized configuration. It was determined that, under certain conditions, a NiFi cluster consisting of three nodes is optimal.

Next-generation mobile networks are becoming more and more demanding at the level of fiber-optic transport networks. Optical networks based on DWDM systems are usually used here. Due to the increasingly used cloud services provided via mobile systems, network traffic is becoming larger and more demanding. The Industrial Internet of Things (IIoT) is an example of a technology that significantly increases the demand for guaranteed network traffic, resulting from the need for the proper functioning of cloud computing and data storage. In order for optical transport networks to efficiently adapt to such requirements, they must become more dynamic and flexible. To achieve this, the grid of DWDM systems must be denser, and the method of managing the optical resources must be made more effective. These problems are significantly reduced by introducing EON technologies. The second paper, authored by Biernacka et al. and titled "Performance Analysis of Automatic Hidden Ligthpaths in Multi-Layer Networks" [31], presents an example of improving the method of managing optical resources in the EON network through the so-called automatic hiding of lightpaths to allocate resources in emergency situations. Thanks to this approach, in a multi-layer network, higher logical layers do not see the selected paths on the optical layer. Simulations were carried out using OMNeT++ software and the Euro28 optical network model consisting of 28 nodes and 82 directed internode connections. Each optical link was set as a resource of 320 slices, where each slice occupies an optical channel with a minimum frequency width of 12.5 GHz. The simulated network operated in IPoEON technology. The logical IP layer was configured in static mode during the simulation. Logical connections were directly assigned to the lightpaths of the EON. Two types of traffic were established in the network, one was static and the other dynamic. Experiments were performed for 10, 20, and 30 candidate paths, and the effectiveness of the Automatic Hidden Lightpath (AHL) method was presented based on the bandwidth blocking probability (BBP) metric as a function of Traffic Load (TL). The effectiveness of AHL refers to the situation when all optical resources are visible at the level of the logical IP layer. Simulation experiments performed in two node selection scenarios clearly show that an increase in AHL candidate paths significantly reduces the BBP value.

The previously mentioned flexible EON networks require optical equipment that allows for quick software change of the physical parameters of the optical signal. This necessity results from the need for more effective use of an optical channel with a specific spectral width when the distance between the transmitter and the receiver has changed. Such a need may arise, for example, from the need to reduce the delay because the service provided via the edge cloud to the 5G/6G mobile network requires maintaining the so-called real time. In order to meet this request, one of the methods will be to establish a connection at the optical layer using several transceivers located closer to the service recipient. Transceiver inserts or optical cards supporting different bitstreams with fixed granularity will greatly increase the flexibility of lightpath selection. This task can be achieved on the optical side when the modulator is complex and reconfigurable enough to be able to change the modulation method on the fly to suit the quality of the optical link and the bitrate demand. In the third paper, authored by Darabi et al. and titled "A Novel Reconfigurable Nonlinear Cascaded MZM Mixer, Amplitude Shift Key Modulator (ASK), Frequency Hopping and Phase Shifter" [32], the authors proposed a solution for the optical system built on two single-arm Mach–Zehnder Interferometers (MZIs). The proposed design allows the MZI mixer optical system to be introduced into a specific functional state (Amplitude Shift Keying (ASK) modulator, Frequency Hopper (FH), Phase Modulation (PM) shifter). The proposed solutions do not allow for a significant change in the order of optical modulation, but they are a good introduction to the construction of such systems. Selecting any of the mentioned functions does not require hardware reconfiguration; all reconfiguration parameters pertain to the electrical states of the control signals, i.e., Radio Frequency (RF) and Local Oscillation (LO). The experiments were carried out at frequencies no higher than 20 GHz. It has been shown that the use of the nonlinear characteristics of the MZI system enables effective control of the transformation of the microwave photonic (MWP) signal in terms of frequency, amplitude, and phase. Compared to microwave (MW) systems, MWP systems are primarily characterized by a much wider bandwidth, which has drawn special attention.

Other optical networks that allow for connecting components of 5G/6G mobile systems are passive optical networks (PONs). Currently, these networks constitute a very important access link between the wide area network and end subscribers. The capacity of modern passive systems and networks is becoming so large that they can and should be used to connect various components of industrial, urban, and infrastructure networks. PON's support for current- and next-generation mobile systems may primarily consist of connecting the 5GC network with the NG-RAN via backhaul (BH), but the implementation of transmission tasks in the fronthaul (FH) and midhaul (MH) domains is also very important. The difference in these transmission services is that backhauling may require long transmission distances exceeding 100 km, while in FH/MH networks, the path length does not exceed 20 km. The fourth paper, authored by Haastrup et al. and titled "A Distance-Weighted Dynamic Bandwidth Allocation Algorithm for Improved Performance in Long-Reach Passive Optical Networks for Next Generation Networks" [33], presents the Distance-Weighted Bandwidth Allocation (DWDBA) algorithm, which significantly increases the efficiency of the use of optical resources in Long-Reach PONs (LRPONs). During planning, the algorithm establishes appropriate weight vectors for the Optical Network Units (ONUs) based on its distance from the Optical Line Termination (OLT) headend. It was assumed that the LRPON network operates on a maximum of four optical channels, necessitating the tuning of the laser as an optical carrier source in accordance with the assumed WDM grid. Simulation results showed that the proposed DWDBA algorithm outperforms the traditional Interleaved Polling with Adaptive Cycle Time (IPACT) algorithm, assuming that the network range does not exceed 100 km. In order to assess the effectiveness of the DWDBA algorithm, two metrics were used, i.e., delay resulting from waiting in the queue and available bandwidth. Simulations were carried out using OPNET modeler software for four distance scenarios, where the differential distance between ONUs did not exceed 50 km.

The future of 5G/6G mobile systems is not only radio communication. The IEEE 802.11bb standard is now available, which is based on optical wireless communication. In this context, there are basically no significant limitations due to the photonic ranges used, but Visual Light Communication (VLC) systems are gaining the most popularity. The optical communication system from the 802.11 family has been referred to as mentioned before Li-Fi. Since Li-Fi systems operate in the near-infrared range, they can successfully cooperate with optical systems based on single-mode and multimode glass fibers. The fifth paper, authored by Kumari et al. and titled "Investigation of OFDM-Based HS-PON Using Front-End LiFi System for 5G Networks" [34], presents an example of a hybrid solution in which Li-Fi communication is effectively combined with the transmission of optical signals in the High-Speed PON (HS-PON) link. It was assumed that the Orthogonal Frequency Division Multiplexing (OFDM) technique, combined with 16-order band modulation and 4-channel multiplexing in the WDM format (for each direction separately), was used in the optical HS-PON link, and a simple 2-order modulation was used in the Li-Fi link. The simulation was performed with the OptiSystem v.21 software. The simulation results were presented in graphs for each of the links, both fiber optic and wireless, as well as for the total. Simulations were performed for various lightpath lengths, ranging from 10 to 100 km. A similar approach was used for the wireless Li-Fi link length up to 20 m. Based on the simulation and analysis results, it can be concluded that the proposed hybrid HS-PON/Li-Fi system can be used in future 5G/6G mobile networks to transport data more effectively with increased resistance to electromagnetic interference.

3. Conclusions

This Special Issue presents five contributions, the topics of which include solutions regarding the use of optical solutions in 5G/6G mobile systems. The presented proposals are not directly related to 5G/6G devices and systems, but they demonstrate the critical importance of optical systems and networks in enabling broadband wireless access systems to function. The contributions raised issues related to improvements in data transmission techniques in PONs and active EONs, proposed automation of optical mixer reconfiguration, outlined the potential of using a new method of wireless access in Li-Fi technology, and highlighted the importance of efficiently managing monitoring data from thousands of optical transceivers to ensure proper functioning of services like network slicing in 5G/6G systems. The future of the applications of optics and photonics in next-generation mobile systems is bright, but subsequent solutions will have to be strongly supported by the use of machine learning and artificial intelligence. These elements were undoubtedly absent in the Special Issue.

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