ADVANCED SERVICE DATA PROVISIONING FOR REAL-TIME MANAGEMENT OF ONGOING CELLULAR COMMUNICATION NETWORKS

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ABSTRACT

A new cost-efficient concept to realize real-time management and monitoring of quality-of-service metrics and other service data in 5G and beyond access network using a separate return channel based on a vertical cavity surface emitting laser in the optical injection locked mode that simultaneously operates as a laser source and a resonant cavity enhanced photodetector, is proposed and discussed. The feasibility and efficiency of the proposed approach are investigated and confirmed by a proof-of-concept experiment when optically transceiving high-speed digital signals with multi-position quadrature amplitude modulation of a radio-frequency carrier.

KEYWORDS

5G and beyond, RoF-based radio access network, real-time monitoring, QoS metrics, bimodal OIL-VCSEL.

1. INTRODUCTION

In recent years, with the maturing of 5G NR systems, the design of access networks (AN) has acquired some significant changes. In particular, the centralized radio access network (C-RAN) that passed from the 4G-LTE network, where interface connects various small cells deployed as remote radio heads (RRHs) to a centralized macro-cell deployed as a baseband unit (BBU) [1, 2], was standardized [3] into the next generation RAN (NG-RAN). Following it, some newer functional blocks, such as a central unit (CU), a distributed unit (DU), and a radio unit (RU) were introduced considered in detail in [4]. The key reason for this transformation was the use of the Common Public Radio Interface (CPRI) with time division multiplexing (TDM) between the BBU and RRH [4]. This approach led to data transfer rates up to hundreds of Gbps, which makes this interface economically unjustified for 5G and beyond. Figure 1 depicts a typical architecture of NG-RAN, where CU, DU, and a set of RUs are duplex connected via fiber-optics communication lines (FOCLs), while RUs and mobile user terminals (UTs) intercommunicate wirelessly.

Generally, as optical networks are evolving to fulfil highly flexible connectivity and dynamicity requirements, and to support ultra-low latency services, it is increasingly important that NG-RAN also provides reliable connectivity and improved network resource efficiency. For this goal, a collection of different types of data from various sources is necessary for applying automation techniques to network management. However, the network must also support the capability to extract knowledge and form perception for performance monitoring and troubleshooting, as well as to maintain network service continuity over a wide range of elements at various levels. Such scalability and flexibility are particularly important for the wide area network, in particular, for streaming telemetry [5]. Moreover, an efficient optical performance monitoring (OPM) design should consider different scenarios including large-scale disaster [6], when a prompt reaction is needed but limited bandwidth is available now.

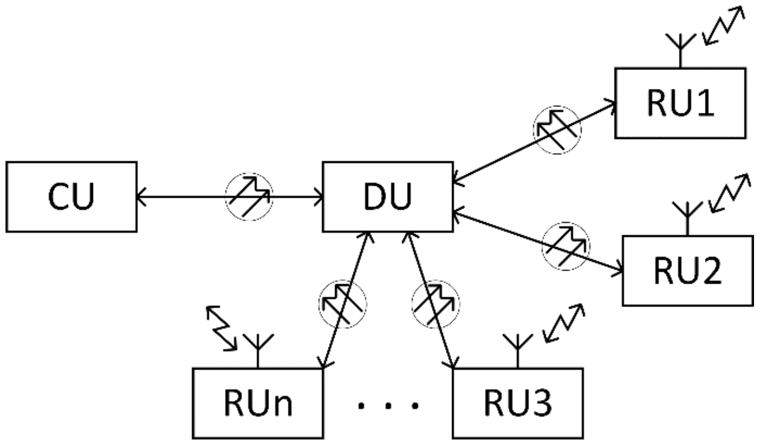


Figure 1. Conceptual block-diagram of 5G's NG-RAN

Projecting the above problem that is common for telecom networks, for the purpose of this paper, we can conclude that in the newer generation, ANs providing the function of low-cost real-time monitoring and the quality-of-service (QoS) metrics are a matter of great importance from the point of view of their maintenance. In this case, the issue can be solved by additionally introducing a special node into the DU circuit (see Fig. 1), which is responsible for the accumulation and processing of monitoring results. However, a more promising solution from the point of view of reducing the total cost and latency, in our opinion, might be the introduction of an additional function from the existing indispensable element of its circuitry, return transmission of the optical signal to the CU, and its processing there. A promising technique for implementing this approach through the simultaneous use of a long-wavelength Vertical Cavity Surface Emitting Laser (VCSEL) in optically injection-locked mode (OIL-VCSEL) as a laser source and a resonant cavity enhanced photodetector (RCE-PD) was proposed in [7] for bidirectional optical communication and recently developed by us [8] referred to microwave photonics circuits.

Elaborating the approach, in this paper after reviewing the modern service provisioning techniques in ongoing optical networks in Section 2, a newer design concept of OIL-VCSEL-based transmitter/receiver, which receives information data from CU via the downlink channel, and simultaneously re-transmits them to RUs and via the uplink channel for processing at CU, is proposed and discussed in Section 3. The feasibility and efficiency of the proposed solution are investigated in Section 4 and confirmed in Section 5 by a proof-of-concept experiment, when optically transmitting a high-speed digital signal with 64-position quadrature amplitude modulation (QAM) of a 5-GHz radio frequency (RF) carrier. Section 6 concludes the paper.

2. MODERN TENDENCIES TO SERVICE PROVISIONING IN ONGOING NG-RANS

With the development of techniques and technologies of 5G NR networks, it became clear that this is not just a new standard for mobile communications. In general, the widespread worldwide introduction of core and access networks of the 5th and subsequent generations in the long term should transform our worldview and lead to a social transformation of the world community, radically changing the principles of communication, architecture, economy, and the level of service of local and global telecom networks. For this purpose, known and new cellular communications concepts, paradigms, approaches, scenarios, technologies, mechanisms, tools, and services are being developed. In particular, they include noted in Introduction NG-RANs, Radio-over-Fiber (RoF)-based mobile backhauls/fronthauls, as well as Enhanced Mobile Broadband (eMMB) [9], Ultra-Reliable Low Latency Communication (URLLC) [10], Massive Machine-Type Communications (mMTC) [11], Internet of Everything [12], Slice-based Networks for Heterogeneous Environments [13], Software Defined Networking (SDN) [14], Network Function Virtualization (NFV) [15] and so on.

The results of the above innovations should lead to significant improvements in the QoS and key parameters of NG RANs. Thus, the recommendation 3GPP TR 38.913 identified the following outstanding key indicators of new generation networks:

- downlink peak data rate up to 20 Gbps with spectral efficiency 30 bps/Hz
- uplink peak data rate up to 10 Gbps with spectral efficiency 15 bps/Hz
- the minimum delay in the radio access subsystem for URLLC services is 0.5 ms, for eMBB services - 4 ms
- the maximum density of the IoT devices connected to the network in urban territories is 1'000'000 devices/sq. km
- autonomous operation of the IoT devices without recharging the battery for 10 years;
- vehicle mobility at a maximum speed of 500 km/h.

Along with these, a critical problem arose related to ensuring the above parameters during the maintenance of realistic NG-RANs through the development of advanced operational principles, approaches, and schemes. In general, advanced monitoring framework of optical networks aimed at the continuous, remote, automatic and cost-effective supervision of the physical layer has to satisfy the basic set of the requirements:

(i) fast and accurate detection of the performance degradation and service disruptions
(ii) accurate track down location of the network failure
(iii) monitoring should be non-intrusive and do not affect normal network operation
(iv) compatible with various types of optical networks.

Besides, to meet the goals of 5G NG and beyond, network infrastructures should facilitate a high level of flexibility and automation. In particular, monitoring and data analytics give rise to estimate accurately the QoS of new light paths anticipating capacity exhaustion and degradations, or predicting and localizing failures, among others to facilitate this automation [16]. At the same time, network operations and management (OAM) should increasingly rely on the ability to stream and process real-time data from network equipment. An integral part of the OAM is to make sure whether the operational conditions are normal or not and intervene, if needed, by quickly recovering and mitigating the occurred problems [17]. The goal to have network management automation and abstraction of open line systems (OLS) could be possible by the software-defined network (SDN) technologies, which require accurate OPM data from the elements of the network [18].

3. DESIGN CONCEPT

Based on the results of the review in Section 2, it can be unambiguously concluded that any existing approach to monitoring the QoS of a FOCLs leads to the complication of the DU circuitry and operation, and consequently to the increase in its cost and the latency of signal transmission via the AN. Therefore, the solution related to the introduction of an additional function to the existing indispensable element of its circuitry, namely the simultaneous use of an OIL-VCSEL as a laser source and a RCE-PD, is promising in principle.

Revealing the proposed concept, Figure 2 demonstrates a block diagram of a communication channel, containing all three functional units of NG-RAN (see Figure 1). It is worth noting that the block-diagram presented in this Figure has three key distinguishing features according to NG-RAN concept. Firstly, at the CU, in order to simplify the circuitry of subsequent units, the conversion of the modulation format of the optical carrier from a baseband (BB) to QAM of RF subcarrier is performed so that the digital signal is then transmitted over FOCLs using a RF equal to the allocated frequencies of the corresponding RU [19]. Secondly, a duplex optical channel is introduced between the CU and DU, where the information signal is transmitted in the downlink direction, and the QoS data signal - in the uplink direction. Thirdly, in the DU, an OIL-VCSEL is connected through an optical circulator, where reflected optical output is transmitted via downlink to the RU, and the detected RF signal with added QoS data is again converted into the optical range using a standard low-cost optical transmitter and returned to the CU for the subsequent processing.

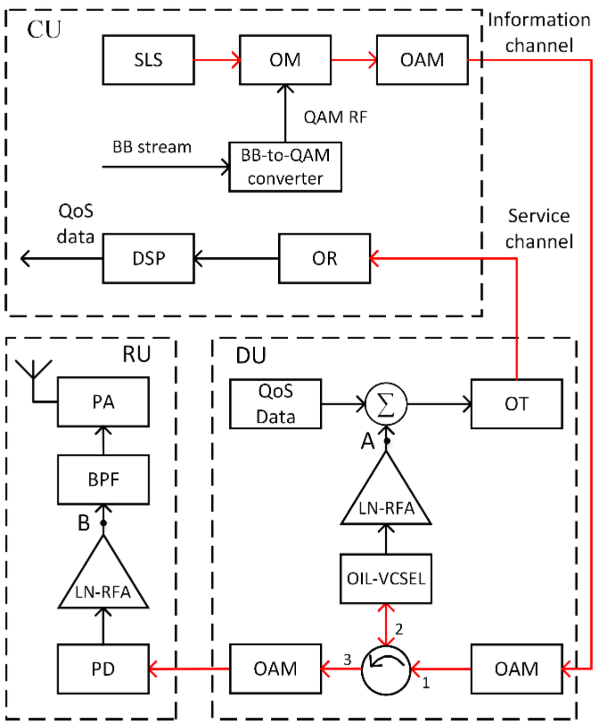


Figure 2. Block-diagram of the proposed duplex communication channel for NG-RAN, where SLS, OM, OAM, DSP, OR, OT, PD, LN-RFA, BPF, and PA stand for semiconductor laser source, optical modulator, optical amplifier, digital signal processor, optical receiver, optical transmitter, photodetector, low-noise RF amplifier, bandpass RF filter, and power RF amplifier (Optical connections are painted in red, electrical connections – in black)

4. DYNAMIC FEATURES OF BIMODAL VCSEL

4.1. Intrinsic direct modulation features of the VCSEL under test

First, in order to select the optimal DC bias point and further comparison, the intrinsic dynamic features of the long-wavelength VCSEL under test operating in free-running mode, are investigated. Figure 3 depicts a testbed for measuring small-signal gain of the directly modulated VCSEL vs the RFs of 0.1-10 GHz at various forward bias currents.

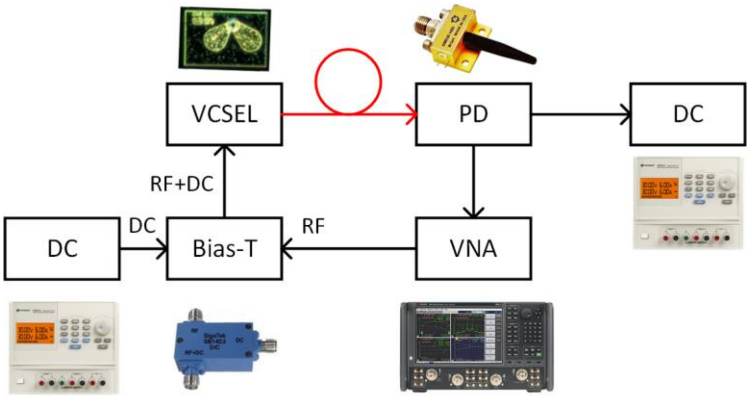


Figure 3. Testbed for studying intrinsic direct modulation characteristics of the VCSEL, where Bias-T, DC, PD, and RF VNA stand for Bias Tee, Direct Current Source, Reference Photodiode, and Radio-Frequency Vector Network Analyzer (Optical connections are painted in red, electrical connections – in black)

The testbed contains a measuring circuit including the direct modulated wafer-fused VCSEL under test (Beam Express, LLC, Switzerland, operating wavelength near 1561 nm) and the reference photodiode (G&H EM169, 20-GHz bandwidth, 0.8-A/W responsivity), as well as accessories such as Bias Tee (Pasternack PE1606, 0.1-MHz…12-GHz bandwidth), and a measuring instruments such as RF Vector Network Analyzer (Keysight PNA-X N5244B) and corresponding DC current source. It should be noted that in current and subsequent studies of this work, the VCSEL in a chip format is used as an object of testing. In this connection, all measurements are carried out on the Probe Station EP6 from Cascade Microtech by a workbench including thermo-electrical cooler for temperature controlling, coplanar RF probe, and fiber-optics probe, which is described in detail in [8].

Figure 4 presents the small-signal gain vs RF characteristics measured by the testbed of Fig. 3.

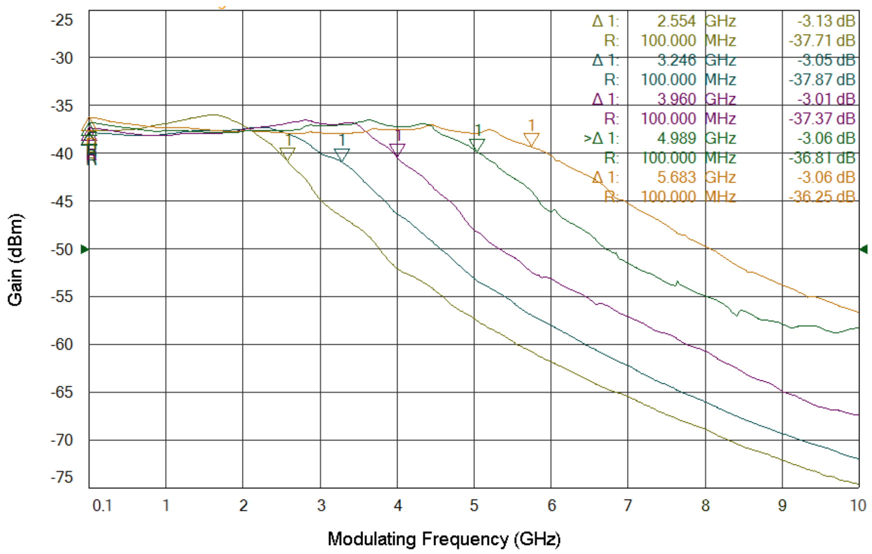


Figure 4. Measured direct modulation characteristics of the VCSEL under test at the bias currents of 4 mA (olive), 5 mA (blue), 6 mA (pink), 8 mA (green) and 10 mA (brown)

As one can see from the Figure, the -3dB modulation bandwidth progressively expands as the bias current increases, reaching from 2.5 GHz at 4 mA to 5.7 GHz at 10 mA.

4.2. Information channel of the proposed concept (OIL-VCSEL in Laser Mode)

Figure 5 depicts a testbed for measuring dynamic characteristics of the Information channel of Fig. 2, where OIL-VCSEL operates in a laser mode. The testbed, besides the tunable semiconductor laser (PurePhotonics PPCL300, 1530-1565-nm wavelength range, 6-13.5-dBm power range) as a master laser, the OIL-VCSEL under test with 6-mA direct current bias as a slave laser, and the reference PD (Finisar XPDV3120, 70-GHz bandwidth, 0.6-A/W responsivity), contains a set of accessories and measuring tools. The latter include Erbium-doped fiber amplifier (home-made, 1530-1565-nm wavelength range, 4-20-dBm output power range, 10-dBm maximum input power, 4-20 dB gain range), optical circulator (Opneti, CIR-3-1550), RF bias-T (Pasternack, PE1BT-1002, 40-GHz bandwidth) as well as corresponding DC current source and RF vector network analyzer (Keysight PNA-X N5244B).

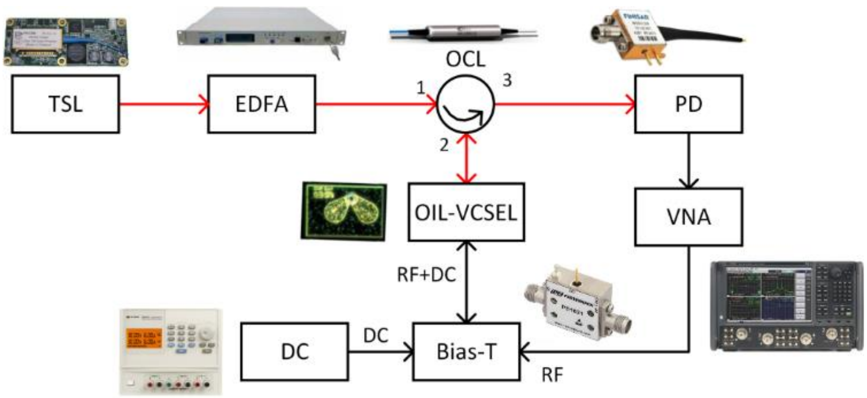


Figure 5. Testbed for measuring dynamic characteristics of the Information channel, where TSL, EDFA, OCL, PD, VNA, and DC stand for tunable semiconductor laser, erbium-doped fiber amplifier, optical circulator, reference photodiode, RF vector network analyzer, and direct current power supplier, respectively. (Optical connections are painted in red, electrical connections – in black)

Figure 6 presents the small-signal gain frequency characteristics at the VCSEL's bias current of 6 mA measured by the testbed of Fig. 5. As one can see from the Figure, the introduction of OIL led to the expansion of the Information channel's -3dB bandwidth to 35.8 GHz with the EDFA output power of 20 dBm (red curve). For comparison, the Figure also shows the intrinsic gain vs RF characteristic of the VCSEL at the same current as in Figure 4 (blue curve), where the -3dB bandwidth is only 4.3 GHz.

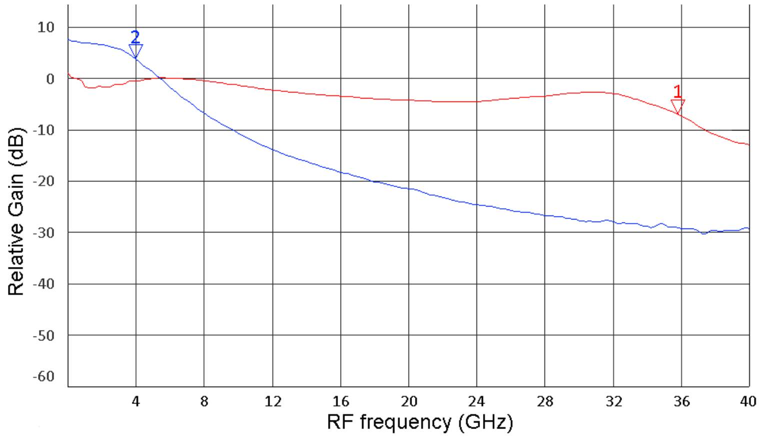


Figure 6. Measured small-signal gain vs RF frequency characteristics of the Information channel, when OIL-VCSEL operates in a laser mode. The markers 1, 2 indicate, respectively: -3dB bandwidth at EDFA output power of 20 dBm and the case of OIL off

4.3. Service channel of the proposed concept (OIL-VCSEL in RCE-PD Mode)

Figure 7 depicts a testbed for measuring dynamic characteristics of the Service channel of Fig. 2, where OIL-VCSEL operates in a RCE-PD mode. The testbed, besides the OIL-VCSEL under test operating at the same direct current bias as in a laser mode and the same master laser (see Fig. 5), contains a set of accessories and measurement tools. The latter includes the external optical modulator (ThorLabs LN05S-FG, 1525-1605-nm wavelength range, 5-dB insertion loss, 35-GHz RF bandwidth), the same EDFA, OCL, bias-T, DC, and VNA as in Fig. 5, as well as Optical Spectrum Analyzer (Yenista OSA20) for real-time monitoring of the emitted spectrum of the OIL-VCSEL under test.

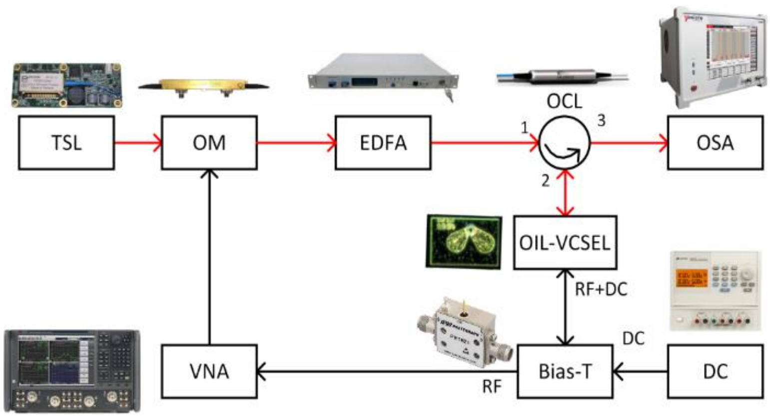


Figure 7. Testbed for measuring dynamic characteristics of the Service channel, where TSL, OM, EDFA, OCL, VNA, DC and OSA stand for the tunable semiconductor laser, optical modulator, erbium-doped fiber amplifier, optical circulator, RF vector network analyzer, direct current source, and optical spectrum analyzer, respectively. (Optical connections are painted in red, electrical connections – in black)

Figure 8 presents the small-signal gain frequency characteristics measured by the testbed of Fig. 7. As one can see from the Figure, the introduction of OIL led to the expansion of the Service channel's -3dB bandwidth to 20.5 GHz with the EDFA output power of 16 dBm (red curve) and up to 27.3 GHz at 20 dBm (blue curve). For comparison, the Figure shows the RF response of the RCE-PD with OIL off (pink curve), where the -3dB bandwidth is only 4.5 GHz.

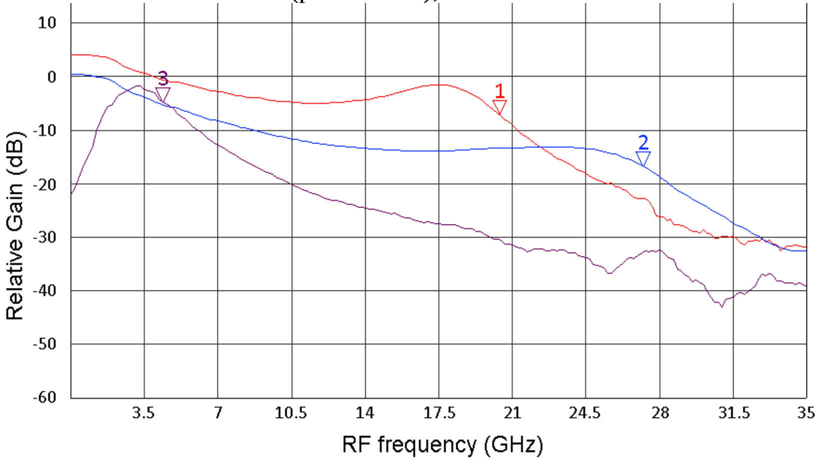


Figure 8. Measured small-signal gain vs RF frequency characteristics of the Service channel. The markers 1, 2, 3 indicate, respectively: -3dB bandwidth at EDFA output power of 16 dBm, the same at 20 dBm, and the case of OIL off

The following outcomes can be drawn from the above results:

- The introduction of OIL led to more than 8-fold expansion of the Information channel's RF bandwidth at the EDFA output power of 20 dBm.
- The introduction of OIL led to a 4.5-fold expansion of the Service channel's RF bandwidth at the EDFA output power of 16 dBm and to a 6-fold increase at its power of 20 dBm.

As a result, due to the expansion of the RF bandwidth, the proposed duplex communication channel for NG-RAN using bimodal VCSEL under study is able to operate effectively not only in the microwave band but also in the millimeter-wave band without using RF up/down converters, in particular, in the 24-27 GHz band allocated for the 5G NR's NG-RAN network.

5. Proof-of-Concept Experiment

To validate the proposed concept a laboratory experiment was realized where a wafer-fused long-wavelength vertical cavity surface emitting laser of RTI Research, LLC in the form of a chip that is optically injection-locked by a master laser, was used. The purpose of the experiment is to confirm the functionality and effectiveness of the block-diagram of a duplex communication channel for NG-RAN described in the Section 3, when optically transmitting a high-speed digital signal with multi-position QAM of a RF carrier. Note that during the experiment the OIL-VCSEL operates in forward DC biased mode without switching to reverse DC bias in photodetector mode as required with a standard pin-photodiode, which is ensured by optical injection locking [8].

Figure 9 shows the testbed for proof-of-concept experiment, the layout of which is based on Fig. 2 with the exclusion of non-essential for the confirmation elements after points A and B. The testbed contains the pin-photodiode (Finisar, BPDV2150: 43-GHz bandwidth, 0.6-A/W responsivity), a pair of low-noise RF amplifiers (Mini-circuits ZX60-542LN-S+: 4.4-5.4-GHz frequency band, 24-dB gain, 1.9-dB noise figure), and two coils of single-mode fibers SMF-28+, as well as measuring tools including Vector Signal Generator (Keysight MXG N5182B) and 4-channel Mixed Signal Oscilloscope (Keysight Infinium MSOS804A).

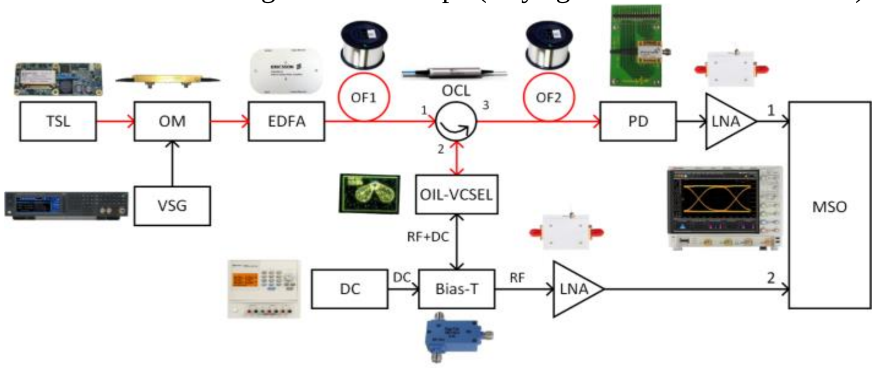
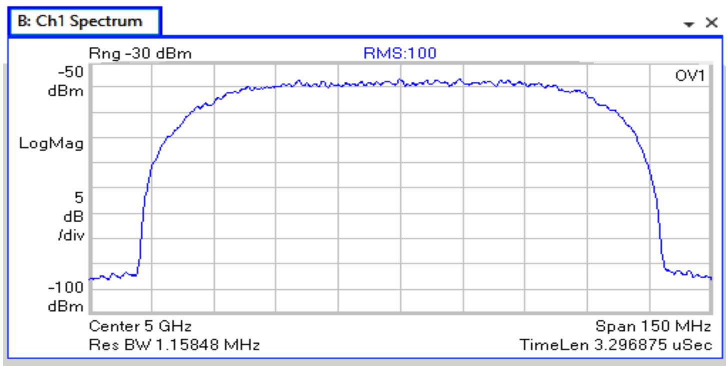
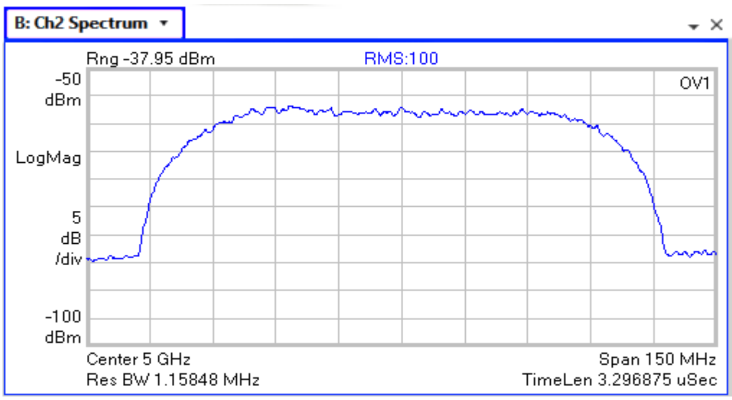


Figure 9. Testbed for the proof-of-concept experiment where TSL, OM, EDFA, OCL, OF, PD, LNA, DC, VSG, and MSO stand for tunable semiconductor laser (master laser), optical modulator, erbium-doped fiber amplifier, optical circulator, optical fiber, photodetector, low-noise amplifier, DC source, vector signal generator, and real-time oscilloscope, respectively. (Optical connections are painted in red, electrical connections – in black)

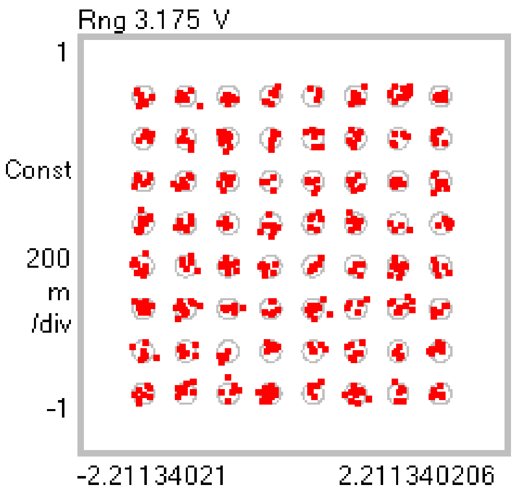
Figure 10 presents the results of the experiment, where optical carrier of the frequency near 192.2 THz is intensity modulated by the 560 Mbps 64-QAM RF signal of 5 GHz. Namely, in Figures 10 (a, b), MSO RF spectra are shown at the inputs 1 and 2, correspondingly. Figure 10 (c) shows the constellation diagram at the input 1 or 2 of the MSO, and Figure 10 (d) shows EVM values vs OF1 length at the inputs 1 and 2 of the MSO.



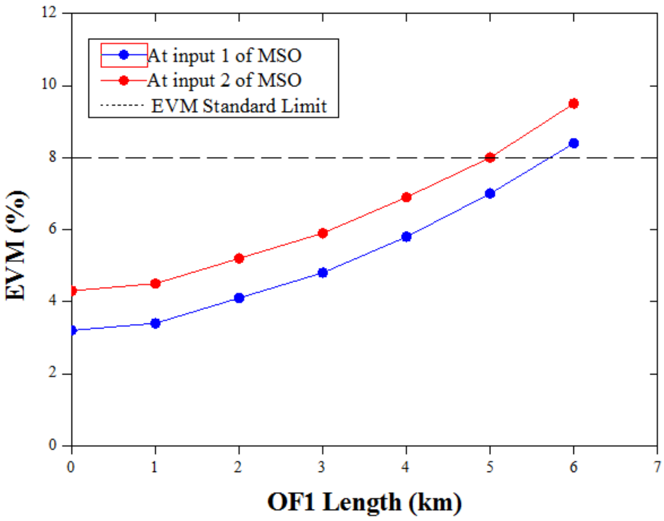
(a) RF spectrum at the input 1 of the MSO



(b) RF spectrum at the input 2 of the MSO



(c) The constellation diagram at the input 1 or 2 of the MSO



(d) EVMs vs OF1 length at the inputs 1 and 2 of the MSO

Figure 10. The results of the proof-of-concept experiment

The outcome that can be drawn from the above results is the following. Leveraging the proposed concept to the NG-RAN block-diagram of Fig. 1, in the DU, the values of error vector magnitude in back-to-back configuration are 3.2% for downlink channel to RU and 4.3% for uplink channel to CU, which is significantly less compared to the standard EVM threshold for 64-QAM of 8% [20]. This maximum acceptable transmission quality is achieved, when the distance between CU and DU is increased up to 5 km, which is quite realistic in a practical 5G access network based on small cell concept.

6. CONCLUSIONS

In this paper, a new cost-efficient concept to realize real-time management and monitoring of quality-of-service metrics and other service data in 5G and beyond access networks using a small-cell architecture is proposed and discussed. The essence of the proposed solution is investigated in detail on the example of a block diagram of a duplex communication channel, including a microcell base station and a functionally split picocell base station containing a central unit, a distribution unit, and a set of remote radio units each connected via optical fiber link. A distinctive feature of the proposed approach, which provides an improvement in the power and cost characteristics, is to use a vertical cavity surface emitting laser in the optical injection locked mode that simultaneously operates as an optical emitter and as a resonant cavity enhanced photodetector. Thanks to this, it becomes possible to transmit information data to a distribution unit via the downlink channel and real-time service data related to the status, quality of service, etc. via uplink channel for processing them at the central unit. The feasibility and efficiency of the proposed solution are confirmed by a proof-of-concept experiment when optically transmitting a high-speed digital signal with 64-position quadrature amplitude modulation of a 5-GHz radio-frequency carrier, which is widely exploited in access networks of fifth-generation cellular communication systems based on Radio-over-Fiber technology and small cell architecture scenario.

Our further research in this direction will focus on a detailed studying the VCSEL-based optical transmission with real-time monitoring function for ongoing 5G and beyond access networks of millimeter-wave band. The reality of such a path was confirmed in this paper. In addition, the fundamental ability to achieve an operating bandwidth of more than 100 GHz due to optical injection locking has already been considered in a number of scientific publications.

ACKNOWLEDGMENT

This work was supported by the Russian Foundation for Basic Research, Grant No. 18-29-20083. The authors are grateful to Beam Express, LLC for providing laser samples.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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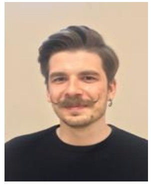

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