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Microwave Photonics and Fiber-Wireless Interface – a Principal Approaches to Design Millimeter-Wave Network Equipment for the Next-Generation Wireless Communication Systems

[Mikhail Belkin, Tatiana Bakhvalova]

***Abstract*—Significant milestones in the way to transform 4G LTE to 5G NR are analyzed in detail. It is shown that a number of the important tasks can be successfully implemented by a microwave photonic or/and millimeter-wave photonic approach to design network and terminal radio equipment. Short descriptions of microwave photonics as an interdisciplinary scientific and technological field, classification of the key elements and devices, and typical layouts of microwave-photonics-based radio-frequency transmitter and receiver units are highlighted. A version of cost- and power-efficient 5G remote station based on millimeter-wave photonic approach is proposed and discussed. As an application example, 5G fiber-wireless network for a regional-level area is design.**

***Keywords*—fifth-generation communication network, Radio-over-Fiber architecture, remote station, microwave photonics, millimeter-wave photonics**

I. Introduction

As known, over last decade the members of worldwide communication research society are seeing an explosion of researches and developments referred to the next-generation communication networks titled as 5G NR [1-5]. Built on the foundation of 4G LTE [6], 5G NR is essentially a novel stage of unprecedented technological innovation with ubiquitous speed connectivity. In the result, it is expected that 5G NR will radically transform a number of industries and will provide direct, super-speed connections between any users and any sensors and devices.

For today, a number of reviews has been published [7, 8], in which an attempt to analyze significant changes in the 5G NR approaches as compared to the existing 4G LTE networks has been made, usually taking into account 3-5 milestones. Developing this topic, the results of the extended analysis based on the study of publications of the last three years are described below. Below, an advanced specification lists 10 significant milestones that a member of the research community should watch out for control.

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Ten Milestones to Transform 4G LTE to 5G NR:

1. Advancing available cellular infrastructure (from macro-cell to femto-cell)

2. Radically updating current spectral limits

3. Expanding network possibilities due to carrier aggregation technique

4. Ultra densification of service areas

5. Mobile data traffic explosion

6. Everything Communication for vehicles

7. Providing More Options with Fixed Wireless Access

8. Using a Mobile Phone as a Hub

9. Using active antenna systems based on multiple MIMO and/or Phased Array Antennas in mm-Wave communication

10. Providing low latency

Analyzing the list, we would conclude that a number of its items (2-6 and 9) can be successfully implemented by solving a global technological task referred to Microwave Photonic (MWP) or/and Millimeter-Wave Photonic (MMWP), as well as fiber-wireless approaches to design network and terminal radio equipment. The rest of the paper reviews recent examples of our research and development in this direction in order to contribute to the development of 5G NR networks.

II. Microwave Photonics Approach

A. *The area of Microwave Photonics*

Microwave photonics (MWP) is a multidisciplinary research and industrial fields encompassing optical, microwave and radio frequency (RF), electrical researchers and engineers [9, 10 and refs. cited there]. This field in the last 30 years has attracted immense interest and generated many new R&Ds from both the scientific community and the commercial sector. Emerging applications for information and communication network (ICN) of Fiber-Wireless (FiWi) architecture, sub-terahertz wireless systems, radar, and electronic warfare systems indicate that MWP is a subject of importance. By common opinion, MWP opens the way to super-wide bandwidth characteristics at lower size, weight,

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and power as compared with traditional ICNs [11]. For example, Fig. 1 depicts typical arrangements of MWP-based software defined RF receiving (a) and transmitting (b) units. As it follows, a photonic circuit is inserted between two microwave electronic chains. For direct and inverse transformations of microwave and optical signals there are two interfacing units at their bounds: electrical-to-optical (E/O) and optical-to-electrical (O/E) converters. Between the interfaces, there are various photonics processing units for switching, distribution, filtration, time-delaying, and up/down frequency conversion of microwave signals in optical domain.

B. Classification of the key microwave photonics elements and devices

There are five basic MWP types of active optoelectronic functional elements and devices, which are depicted in Fig. 2:

• optical-to-electrical converter (Fig. 2, a), for example, photodiode;

• electrical-to-optical converter (Fig. 2, b), for example, semiconductor laser;

• optically controlled microwave sensor (Fig. 2, c), for example, microwave generator which parameters (frequency, output power) depend on optical signal;

• converter of optical signal (Fig. 2, d), for example, optical modulator, laser amplifier;

• sensor or converter of microwave signal (Fig. 2, e), for example, optoelectronic oscillator, optoelectronic mixer,

In addition to the above listed types of optoelectronic functional elements and devices, there are two types of devices based on all-optical interaction that can be effectively applied in MWP equipment:

• optically pumped converter of optical signals (Fig. 2, f), for example, Erbium, Raman and Brillouin fiber amplifiers;

• optically pumped sensor of optical signal (Fig. 2, g), for example, the Erbium fiber oscillator.

Common distinctive feature of all above-mentioned devices and functional elements is their operation in C- (1530...1565 nm) and/or L- (1565...1625 nm) spectral ranges, as specified by ITU-T. The main reasons for such a choice are the lowest losses in silica fiber, the widest operation spectral range and availability of low cost and high performance fiber amplifiers for compensation of losses. These elements and devices represent the principal building blocks for creation of essentially new devices and units, which can significantly improve the key technical characteristics of modern microwave and mm-Wave wireless electronic means, such as throughput, latency period, operating frequencies, bandwidth, dynamic range, electromagnetic compatibility, etc.

III. Millimeter-Wave Photonics Technique in Fiber-Wireless interfaced 5G Wireless Networks

To implement effective radio communication within small cell architecture (item 1 of Introduction), a number of leading countries developed a prospective spectrum including mm-Wave bands up to 100 GHz. Fig. 3 exemplifies USA assignation ranged from 27.5 to 95 GHz [13].

As shown in a large number of studies [5, 14, 15], mm-Wave 5G network infrastructure must be share with a lot of small service zones controlled by the corresponding remote station (RS). In order to avoid inter-interference in these zones, one of the feasible approaches is to provide the RS with a beam-steerable phased array antennas (PAA).

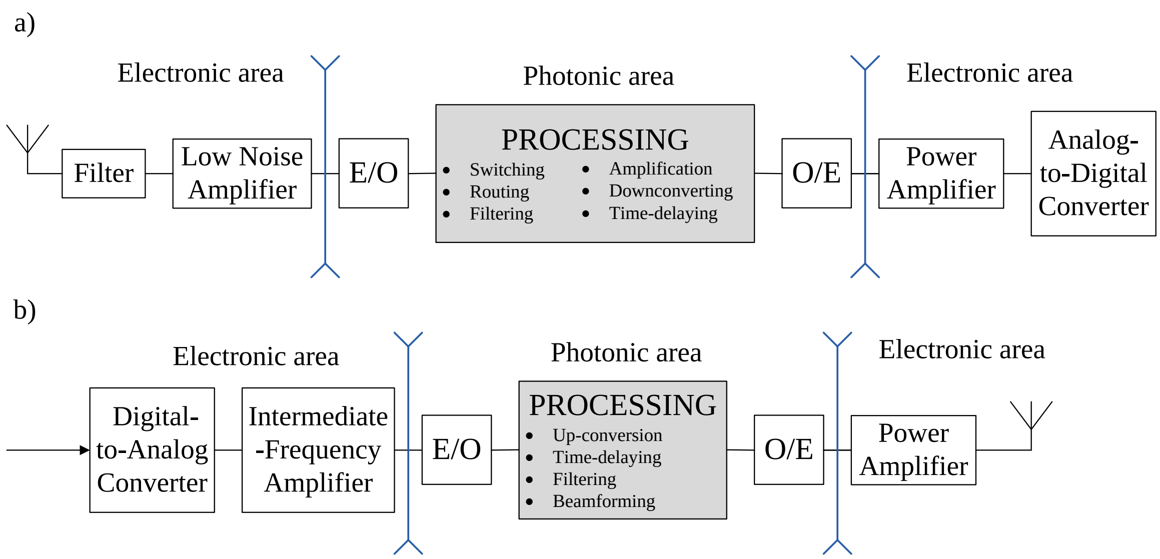

Figure 1: A typical arrangement of MWP-based software-defined RF receiver (a) and transmitter (b).

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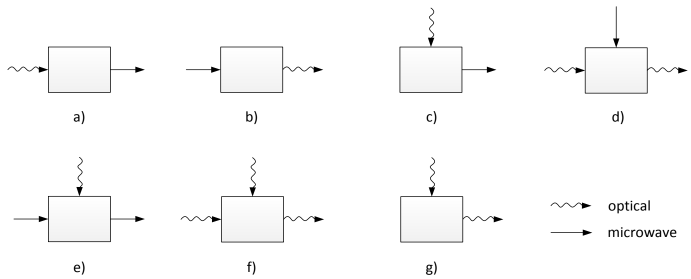

Figure 2: The classification of functional elements and devices for microwave photonics technology.

Generally, to form directional beams for transmission and receiving beams from adjacent STs and RSs, mm-Wave RS must use PAA with hundreds of antenna elements. Combining mm-Wave band and fiber-wireless (FiWi) network architecture is one of promising way to deliver intensive digital traffic with seamless convergence between optical backhaul and wireless fronthaul. In addition, FiWi technique allows converting directly a lightwave spectrum to mm-Wave radio spectrum using a simple MWP-based up-conversion scheme [16], which is important to keep the remote cells flexible, cost-effective, and power-efficient. Fig. 4 exemplifies a mm-Wave FiWi architecture, which consists of a central office (CO), remote stations (RS) and wireless subscriber terminals (ST). CO is interactively connected with RS through fiber-optic cable, and RS is interactively connected with ST through wireless link. A typical position of RS is in the center of the service area; that is, for omnidirectional covering, four PAAs with an azimuth of 90 would be an optimal decision.

IV. Cost- and Power-efficient Remote Station Based on MMWP Approach

Fig. 5 depicts an example of the layout for the RS operating inside 28-GHz spectral band [17] assigned for 5G networks in USA (see Fig. 3). In accordance to the standard design concept for remote stations of wireless networks, it comprises of downlink channel (from CO-started fiber-optic link to ST-finished wireless links in Fig. 4) with RF carrier frequency up-conversion (18.4-to-27.6 GHz) and uplink channel (in return direction) with RF carrier frequency down-conversion (28.3-to-14.15 GHz). Namely, the downlink channel includes first photodetector (PD) as an optical-to-electrical converter, low-noise amplifier (LNA), RF-coupler (RFC), optically injected long-wavelength vertical cavity surface emitting laser (LW-VCSEL) [18] in, so called, period-two (P2) state [19, 20] as a photonic up-converter, optical coupler (OC), one more PD as the second optical-to-electrical

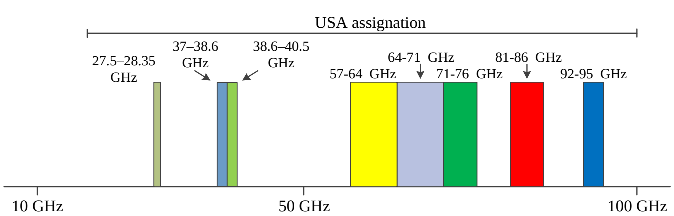

Figure 3. 5G's mm-Wave spectrum allocation of USA assignation.

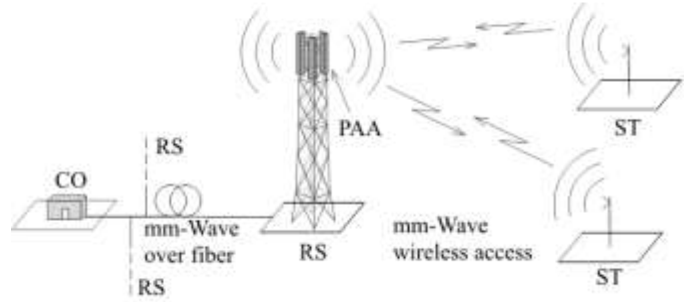

Figure 4. An example of mm-Wave RoF architecture.

converter, RF band pass filter (BPF) as a selector of 27.6 GHz, power amplifier (PA), diplexer, and common antenna (A). Besides, the uplink channel includes antenna, diplexer, LNA, RFC, the same LW-VCSEL in P2 state as a photonic down-converter, and OC. Note that the output optical signal contains two sub-carriers at 14.15 and 27.6 GHz. The reason to translate a second RF carrier to CO is in possibility to monitor remotely the operating status of the uplink channel from corresponding ST.

An important peculiarity of the layout has been proposed is an additional fiber optic link from CO, over which remote optical reference for optical injection locking (OIL) of LW-VCSEL is distributed. The main advantage of using LW-VCSELs in P2 state are: (i) enlarging direct modulation bandwidth up to mm-Wave band; (ii) application versatility (up-converter and down-converter have the same block diagram); (iii) conversion loss independence of the position of microwave frequencies within the operation band (absence of the inherent effect of increasing conversion loss with frequency for standard microwave mixers); (iv) design simplicity and flexibility; (v) lower power consumption of the VCSELs (5-10-fold lower than that of edge-emitting lasers); and (vi) lower required output power of master laser (few dBm instead of 15-20 dBm for edge-emitting lasers).

V. Example of Building 5G Network for Regional-Level Area

At last year CCIT conference, we presented a report where the building principles of the 5G network in the metropolitan area were reviewed. The city of Moscow that is the capital of Russia, was chosen as a specific example. This time, the building principles of 5G network for regional-level area are

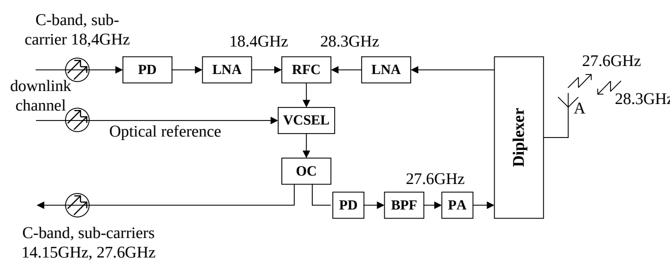

Figure 5. Layout of remote station with direct modulated optically injected LW-VCSEL in P2 state.

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highlighted. The so-called Golden Ring of Russia was chosen as a specific object of research.

Fig. 6 depicts the arrangement of Golden Ring of Russia, which includes in addition to Moscow, eight Russian cities. The Golden Ring of Russia is a tourist route that passes through the ancient cities of North-Eastern Russia, in which unique monuments of Russian history and culture and centers of folk crafts have been preserved. The route passes through the ancient Russian cities that have made a significant contribution to the history of the country and its culture. All cities shown on the Figure were historically part of Vladimir Russia.

In this project, the super-speed digital fiber-optic network of ring configuration is located along transport highways in full accordance with Fig. 6. At the same time, in each city a transport network node (TNN) is introduced, which implements the interface between the baseband digital system and the system of FiWi architecture. Further, the city of Rostov the Great was chosen as a city for a detailed study of the principles and schemes for designing the 5G network. Rostov is the pearl of the Golden Ring, uniting the oldest cities of Russia. It is one of the oldest cities in Russia was mentioned in the Tale of Bygone Years, the Russian Primary Chronicle - in the annals of 862. The significant cultural potential of the city made it one of the major centers of tourism and pilgrimage. Rostov is included in a special program of cooperation between the Council of Europe and Russia for the preservation of historical and cultural heritage.

Fig. 7 depicts 5G's backhaul fiber-optics network consisting of one macro-cell with service diameter of 5.3 km, inside which 24 micro-cells of service diameter near 1 km are located. The red line marks the boundaries of the city.

Figure 6. Arrangement of the Golden Ring of Russia.

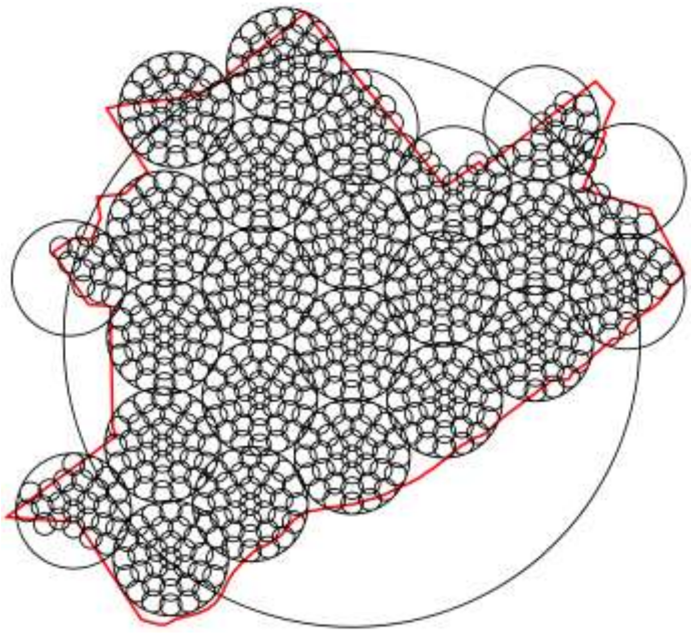

Figure 7. 5G's backhaul fiber-optics network of Rostov city.

Introducing a smaller partition, Fig. 8 shows a typical micro-cell diagram containing 33 pico-cells with a 200-m service diameter. In the center of each pico-cell a remote station (RS) is located (see Fig. 4), which is an interface between fiber and wireless network sections. It is indicated by a fat point in the Fig. 8. An example of a RS layout based on MMWP approach is shown in Fig. 5. All RSs are interactively interconnected via fiber-optic lines, forming a communication structure of the type 'Fully connected network'.

VI. Conclusion

In the paper, 10 significant milestones in the way to transform 4G LTE to 5G NR are proposed and analyzed. Follow them, it is shown that the important tasks referred to

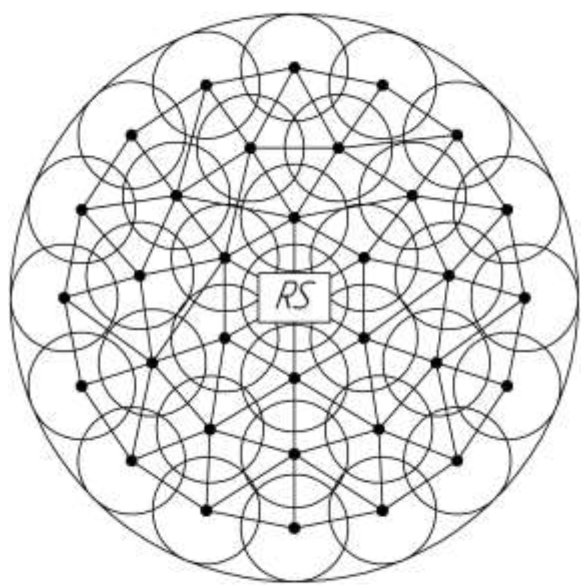

Figure 8. Diagram of pico-cells inside one micro-cell

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expanding the available spectral allocation up to 100 GHz can be successfully implemented designing needed network and terminal radio equipment based on microwave photonic or/and millimeter-wave photonic, and fiber-wireless approaches. For verification, a general description of microwave photonics, classification of the key elements and devices, and typical layouts of microwave-photonics-based radio-frequency transmitting and receiving units both including the same chain consisting of electronic frontend, photonic processing area between RF-to-optical and optical-to-RF converters, and electronic backend are highlighted. A version of cost- and power-efficient 5G remote station in the range of 27-28 GHz in according to 5G USA assignation, with the core founded on optically injection locked long-wavelength vertical cavity surface emitting laser (LW-VCSEL) in period-two state, is proposed and discussed. As an application example, the arrangement diagrams of the backhaul fiber-optics network for the Golden Ring of Russia and fiber-wireless fronthaul network for Rostov the Great city are described.

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