Photonics Defined Radio
A New Paradigm for Future Mobile Communication of B5G/6G

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Keywords: Fibre Optics Links and Subsystems, Radio Frequency Photonics, Photonic Integrated Circuits, Coherent Communications, Optical Signal Processing, Radio Access Network, Beyond 5G.

Abstract: Photonics defined radio, a new and possibly standardized paradigm, is proposed, converging integrated coherent optics, integrated microwave photonics and photonic DSP, and expected to dominate the designs of future communication and sensing systems. The applications of photonics defined radio are also discussed in the next generation cloud-based radio access network (CloudRAN), sensing and communication integrated system, as well as artificial intelligence radio.

1 INTRODUCTION

Optics and photonics have made many progresses in the past years, especially in the areas of integrated coherent optics, integrated microwave photonics, optical frequency comb and photonic digital signal processing.

In 2006, Infinera reported the first commercially deployed and indium phosphide (InP) based large-scale photonic integrated circuits (LS-PICs) of coherent optics (Jacco Pleumeekers et al, 2006). This breakthrough brought optical coherent transmission back. Nowadays, coherent optical transmission follows the trend migrating from long haul market into metro and access arena with main applications in mobile fronthaul of 5G/B5G. To use linear phase modulation (PM) and coherent detection (CD), high linear RF photonic or coherent radio over fibre (CRoF) links have extensively been realized. In particular, to employ a novel attenuation counter-propagating optical phase-locked loop (ACP-OPLL) demodulator the ultra-high linear CRoF links have been obtained, and to use a hybrid integrated or a monolithically integrated ACP-OPLL, 140dB/Hz$^{2/3}$ spurious free dynamic range (SFDR) over 1GHz bandwidth has been expected (S. Jin et al, 2014). As a result, CRoF shows a promising potential to future true cloud-based 5G/B5G applications.

Integrated microwave photonics (IMWP) has become the most active area of current research and development in microwave photonics. Based upon various material platforms such as indium phosphide (InP), silicon on insulator (SOI), Si photonics and silicon nitride (Si3N4), several particular functionalities and sub-systems have be realized (David Marpaung et al, 2014), including tunable filtering, optoelectronic oscillation, true time delay, frequency up and down conversion, etc. In the mode of monolithic or hybrid photonic circuits, IMWP is evolving towards the so-called application specific photonic integrated circuits (ASPICs) where a particular circuit and chip configuration are designed to optimally perform a particular functionality. Furthermore, a photonic system-on-chip (PSoC) is being developed, such as EU HAMLET project which is the joint development of a new kind of photonic frontend for future 5G/B5G mobile networks in the frequency range of 28GHz, and using hybrid photonic integration technology to interface seamlessly the optical fronthaul and radio access of the remote antenna units (RAU) (*http://www.ict-hamlet.eu/*).

Coherent light source with wider spectrum is critical to IMWP, CRoF and photonic digital signal processing (DSP). Optical frequency comb (OFC) is a revolutionary advance in broadband coherent source. However, the bulk OFCs based on existing mode-locked lasers have limited applications in real-world due to their size, weight, power and cost. Electro-optic or parametric frequency combs such as Kerr micro-combs have later evolved based upon

Baiqing, Z., Xiaohong, Z., Xiaotong, L., Jianli, W. and Senlin, Z.
Photonics Defined Radio - A New Paradigm for Future Mobile Communication of B5G/6G.
DOI: 10.5220/0006551501550159
In *Proceedings of the 6th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2018)*, pages 155-159
ISBN: 978-989-758-286-8

chip-compatible monolithic micro-resonators (J. E. Bowers et al, 2016). Together with PIC, integrated OFC provides the opportunity for applications in the fields such as optical arbitrary waveform generation (OAWG), microwave photonic signal processing, optical DSP, dense wavelength division multiplexed coherent transmission systems and future 5G/B5G large-scale antenna systems in which an OFC-based photonic frontend array will be an ideal option for RF beam forming and steering.

To overcome the timing jitter and bandwidth limitations of electrical ADC, photonic analog-to-digital conversion (PADC) has been the subject of extensive research in recent years (Thomas R. et al, 2015). Nowadays, in order to efficiently connect the optical sampling module and eliminate the electrical device limitation, it is essential to realize the all-optical operation in both quantization and signal processing. Extensive optical quantization and photonic DSP schemes have been proposed. The proposed photonic DSP is capable of performing reconfigurable signal processing functions including temporal integration, temporal differentiation and Hilbert transformation (Weilin Liu et al, 2016). The demonstration of photonic DSP also implies that the chip-scale fully programmable all-optical DSP has great potential for achieving a photonics defined system.

In spite of above mentioned advances, the applications of integrated optics and photonics in radio systems are still too small and fragmentary. On one hand, these technologies belong to different disciplines and technological areas, as a result, there are almost as many technologies as applications and, due to this considerable fragmentation, the market for many of these application-specific technologies is too small to justify further development into low-cost industrial mass-volume manufacturing processes (Daniel Pérez et al, 2016). On the other hand, MWP as a complementary method for designing radio systems was proposed early several decades ago, and was determined that it is difficult to become a dominate paradigm for designing radio systems. Moreover, at the present state MWP is addressing lower volume market, hence lower volume PIC productions. These are the aspects that may force PIC technology players to take a different approach to integrated MWP (Daniel Pérez et al, 2016). However, the next generation of radar systems and B5G even 6G mobile networks, in which the systems will be with higher carrier frequencies for smaller antennas and broadened bandwidth for increased resolution, need a new paradigm and disruptive technology.

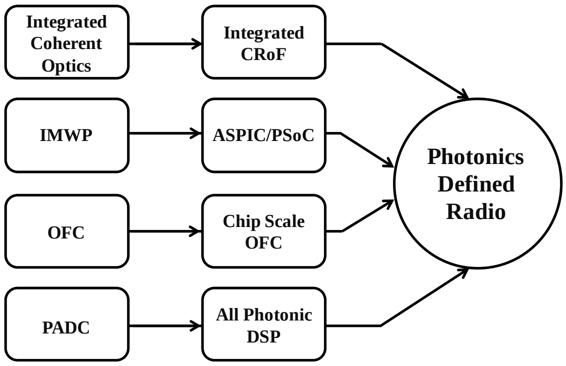

Figure 1: Convergence and evolution of PDR.

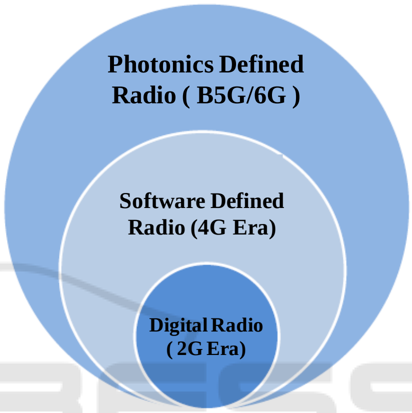

Figure 2: Key enabling technologies via intergenerational evolution of mobile networks.

In addition, standardization is an important aspect for new technology introduction into the market and support of a healthy ecosystem. To overcome the above problems, in this paper, we propose a new and possibly standardized paradigm named **photonics defined radio** (also called photonics-based radio or photonic radio), converging integrated CRoF, IMWP and photonic DSP, and expected to dominate the designs of future radio and sensing systems. Referred to digital radio for 2G and software defined radio for 4G, photonics defined radio (PDR) will be the fundamental enabling technology of B5G/6G. Inspired by large scale RAN market, PDR will drive and promote mass production and development of PIC. Fig.1 and Fig.2 show the convergence and evolution of PDR, the key enabling technologies via intergenerational evolution of mobile networks, respectively.

2 THE CONCEPT AND ARCHITECTURE OF PHOTONICS-DEFINED RADIO

The key idea of PDR is to build an open, standardized, modular radio system by analog and digital photonic signal processing. PDR has also the features of ultra-broadband spanning from microwave to light, EM immunity and flexibility. Fig.3 shows the function model of PDR. The photonic frontend (PFE) with optional RF frontend (RFE) performs the transmission, reception and conversion of light or RF signal. The photonic engine (PE) implements the signal generation and processing in optical domain. The functions of spectrum computing (SC) are that, they act as electronic arbitrary waveform generation (eAWG), symbol generation, electronic DSP and deep cognitive radio engine. Configurations can be programmed to offer the main functionalities required for PDR by software and control module. Fig.4 is the network architecture of next generation CloudRAN based on PDR.

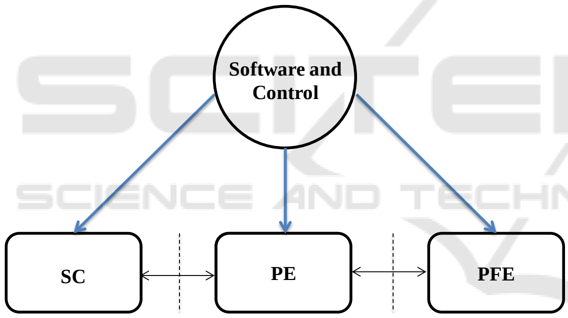

Figure 3: The function model of PDR.

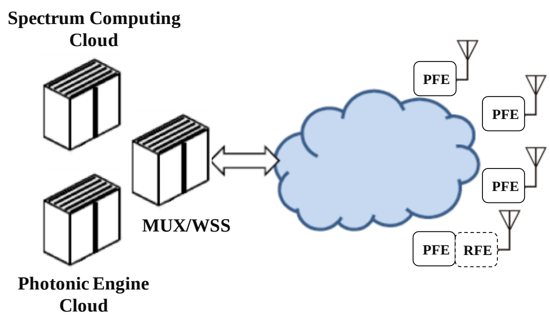

Figure 4: The network architecture of NG CloudRAN based on PDR.

3 THE APPLICATIONS OF PHOTONICS-DEFINED RADIO

3.1 All Photonic, All Coherent and Full Spectrum CloudRAN

Fig.5 is the building blocks of PE of PDR. In PE, the interface between PE and PFE is transparent coherent optical interface, and its Tbit-capacity is high enough to support a true cloud-based RAN. On the other hand, the signal processing in SC is electrical coherent processing, so PDR is a hierarchical coherent system in RF and optical domains. Fig.6 shows an all photonic RAU or PFE with multi-antennas. At the downlink, the optical signals are forwarded to the integrated coherent receivers (ICR), where they are detected and processed. Due to high-power output of the uni-traveling carrier photodetector (UTC-PD) (Zhanyu Yang et al, 2015), arrays of UTC-PD convert the optical signals to electrical signals that are directly used to drive the array antenna elements. At the uplink, the array antenna elements feed RF signals to an array of graphne-based electro-absorption modulators (GP-EAMs), in which RF signals are up-converted to optical signals by optical IQ modulation (IQM). At last, the optical signals are multiplexed and sent to the optical network. Thus, all photonic PFE and PE build an all photonic CloudRAN. In addition, arrays of ICR and GP-EAM can slice the RF and optical spectra in a very large bandwidth, resulting in a full spectrum CloudRAN.

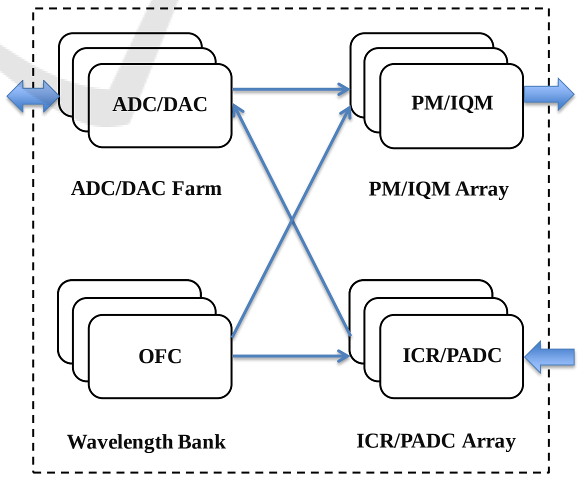

Figure 5: The building blocks of PE of PDR.

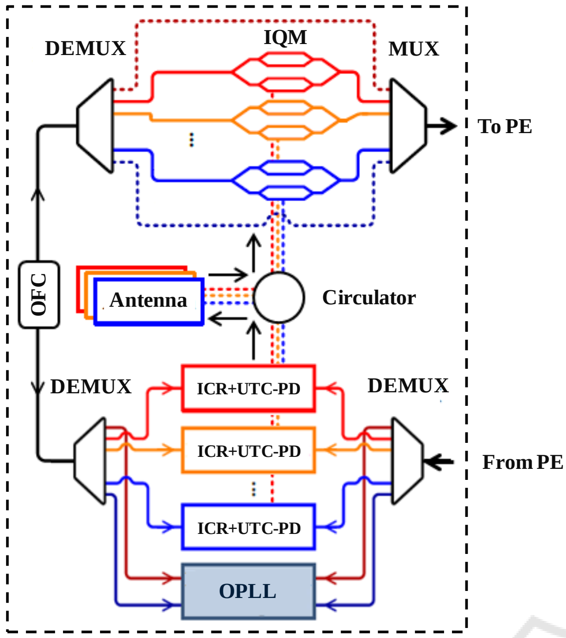

Figure 6: All photonic PFE or RAU with multi-antennas.

3.2 Radar, LiDAR and Communication Integrated System

In Fig.6, if the antenna array is arranged as a hybrid antenna array of RF and optical antennas, PFE can be used as RF and optical wireless systems, simultaneously. For RF wireless systems, Radar and RF wireless communication are typical applications. For optical wireless systems, LiDAR and coherent free-space optical (FSO) communication are practical applications. Spanning from RF to optical, PDR can achieve a hyper-spectral integrated system for sensing and communication applications.

3.3 Artificial Intelligence Radio - RadioAI

A significant challenge for future cognitive radio systems is to instantaneously analyze RF signals over a extreme broadband to 100GHz or more, in real time without any scanning in frequency, and without any prior knowledge of the signals, carrier frequency as well as modulation format (K. D. Merkel et al, 2014). Due to the limited bandwidth and less agile hardware platform, conventional cognitive radio faces a big gap between flexible, effectively building block and the deployment in mobile networks. PDR provides extreme broadband and even full spectrum capacity, so it will be an ideal platform of future cognitive radio for B5G/6G. In addition, recent advances in machine learning (ML) have made possible significantly different approaches in RF signal processing, spectrum mining and RF mapping. Unfortunately radio signal processing has been notably absent from much of this recent work, but the potential for applications of recent advances in machine learning to the radio domain is enormous (Tim O'Shea and Nathan West, 2016). Combining PDR with machine learning, a novel framework of future cognitive radio named **artificial intelligence radio - RadioAI** (or RadioML/RadioDL) will be a key paradigm and enabler of B5G/6G. Extreme wideband of PDR generates a great amount of data from spectrum sensing, providing big and well curetted datasets to allow ML to effectively train and learn with large parameter spaces. Fig.7 shows the framework of RadioAI based on PDR. A PDR is used as an extreme broadband radio platform implemented with open interface that can be programmed to transmit and receive a variety of waveforms. A RadioAI engine in spectrum computing cloud is composed of a datasets, inference engine, and a learning engine. A well-defined API dictates communication between the RadioAI engine and the PE/PFE.

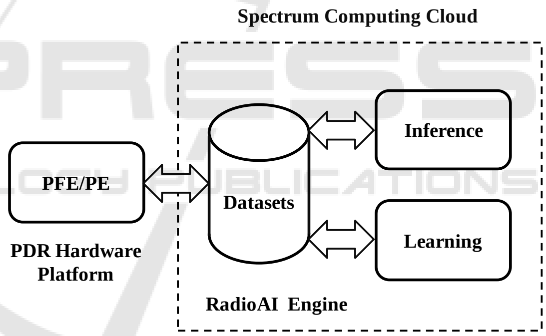

Figure 7: RadioAI framework based on PDR.

4 CONCLUSIONS

In summary, the applications of integrated optics and photonics in radio systems are still too small and fragmentary due to the fragmentation of disciplines and technologies. And the next generation of radar systems and B5G/6G mobile networks need a new paradigm and disruptive technology. Therefore, we propose the concept of photonics defined radio, a new and possibly standardized paradigm, converging integrated coherent optics, integrated microwave photonics and photonic DSP, and expected to dominate the designs of future communication and sensing systems. The potential applications of photonics defined radio are also discussed, including next generation CloudRAN, sensing and communication integrated system, as well as artificial intelligence radio – RadioAI.

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