Key Enabling Technologies for the Post-5G Era: Fully Adaptive, All-Spectra Coordinated Radio Access Network with Function Decoupling

You-Wei Chen, Rui Zhang, Chin-Wei Hsu, and Gee-Kung Chang

With the rapidly growing bandwidth demand for wireless applications, new system technologies related to post-5G are emerging. The authors discuss an all-spectra fully adaptive and coordinated radio access network (RAN). By employing a fiber-wireless integration and networking architecture, all data-carrying channels could be aggregated in the same fiber access infrastructure.

Abstract

With the rapidly growing bandwidth demand for wireless applications, new system technologies related to post-5G are emerging. In this article, an all-spectra fully adaptive and coordinated radio access network (RAN) is reported and discussed. By employing a fiber-wireless integration and networking architecture, all data-carrying channels could be aggregated in the same fiber access infrastructure. This enables a coordinated RAN with function decoupling, in which lower RF, 5G New Radio (NR), sub-THz, and even lightwave are employed; also, different types of services are delivered depending on their physical layer properties. Promising scenarios are discussed, such as integrated access of wireless NR-free space optical (FSO) backhauling and indoor systems via visible light communication (VLC) and efficient NR beamforming aided by VLC positioning system. The former use case can enhance the network throughput and reliability. This is because both FSO and NR can support high channel capacity due to their abundant bandwidth. Meanwhile, with the advancement of novel DSP techniques, the stability of the NR-FSO link under diverse weather turbulences or suffering from burst mode interference can be enhanced. The latter scenario provides an alternative solution for high-speed data link and a simplified beam management via the VLC-aided positioning system. VLC can concurrently provide ubiquitous indoor illumination, data transmission, and positioning. With the help of artificial intelligence algorithms, a VLC-based precision positioning system can provide a location accuracy of < 1 cm, and it is able to meet the narrow beam size of the NR beamformer in a 3D model. Therefore, it is foreseeable that an all-spectra function decoupled RAN can serve as a unified network platform to support all wireless applications while optimizing system throughput, channel condition, network coverage, and software/hardware complexity for post-5G mobile data networks.

Introduction

Since the standardization for 5G is coming to its final phase, network operators have started their 5G trials around the world, and 5G is launching commercially in 2020. Therefore, both academic and industrial researchers have started to think and plan for 6G, which is envisioned to be deployed by 2030. Research activities are thus emerging [1, 2]. In the 5G era, multiple user-specific scenarios are introduced to meet the extremely diverse requirements, such as 4K/8K video streaming, augmented reality (AR), virtual reality (VR) and mixed reality (MR) wearables, cloud gaming, Industrial IoT (IIoT), and remote healthcare. The requirements could be mainly classified into three well-known categories: enhanced mobile broadband (eMBB), ultra-reliable and low-latency communication (URLLC), and massive machine type communication (mMTC). Moreover, the driving force for the first phase of post-5G and 6G could be the extremely data-intensive wireless broadband services. For instance, to further extend the user experiences from the AR/VR to extended reality (XR), research groups are proposing fully immersed experiences of five senses (i.e., sight, hearing, touch, smell, and taste) as well as holographic society [3]. Therefore, the data demand is going into another level from the 5G era.

5G NR and Promising Extension

In the 5G standardized body, to deal with the rapid increment of data demand, researchers pushed the radio carrier frequency to the millimeter-wave (mmWave), named 5G New Radio (NR), to conquer the over-crowded spectrum resource below 6 GHz. In 3rd Generation Partnership Project (3GPP) Rel-15, frequency range two (FR2) covers up to 52.6 GHz; while in the incoming Rel-17, frequencies between 52.6 GHz and 71 GHz are especially interesting for high data rate communications. Thus, as 6G is coming, it will intuitively accommodate the higher frequency band for the dramatically increased data requirement. In that sense, sub-THz and optical wireless communication (OWC) are considered as two of the promising extensions from the 5G era. Meanwhile, to deliver diverse services seamlessly to wireless users, fiber-wireless integration and networking (FiWIN) is extremely important to make 5G and 6G a reality. As shown in Fig. 1, all service data from different RF carriers and even lightwave

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can be accommodated and aggregated in a radio access network (RAN) through the same fiber infrastructure.

Network Function Decoupling

For post-5G with the extension of NR and free-space optics (FSO) carriers, one significant advantage is network function decoupling, in which one service can be concurrently supported via multiple coordinated carriers. Therefore, each carrier can efficiently deal with part of the service requirements to enhance the user experience or provide a complementary link for data delivery. For instance, as the operating RF frequency continues to increase, the transceiver becomes more expensive with lower availability. However, with the maturity of the FSO devices and techniques, we can increase the operating frequency up to THz. Visible light communication (VLC) or light fidelity (Li-Fi) can concurrently provide indoor data transmission and user equipment (UE) positioning. Thus, considering different physical properties of carrier frequencies, an all-spectra coordinated RAN could manage various services depending on their functionality, bandwidth, and coverage requirements. By combining the advantages of different bands and utilizing all available spectra, including low RF, NR, sub-THz, and even lightwave, different types of data traffic can be accommodated efficiently.

In this article, we review some of the breakthroughs in the FiWIN research center of an all-spectra coordinated and function decoupled RAN; in particular, integrated wireless NR-FSO backhauling/fronthauling for outdoor environments, OWC for indoor applications, and VLC aided NR beamforming, as shown in Fig. 2. For economical 5G evolution, the fixed wireless access via 5G-NR is first deployed to provide ultra-high data rate wireless fronthauling/ backhauling, which is an alternative approach to facilitate densification of 5G remote radio units (RRUs) in urban areas or in some areas where fibers are unavailable. However, relying on a single RF carrier of 5G-NR cannot guarantee a reliable wireless connection, since a high frequency channel is sensitive to weather turbulence (e.g., rain) or some burst interference. In this case, we propose an NR-FSO integrated system architecture with advanced digital signal processing (DSP) techniques [4, 5] to enhance the reliability under different weather and channel turbulence. On the other hand, a VLC illumination system can provide extra functionalities such as high-speed indoor downstream and precise indoor positioning. It is useful to IIoT applications and coordinated signal control. With the help of a visible light positioning (VLP) system, establishing 5G-NR connection from RRU to UE can have lower latency and more efficiency in its operation complexity as well as extend its network scalability.

Opportunities of OWC and an integrated NR-FSO access for post-5G and 6G deployment are discussed in the next section. Later, we review several indoor deployment scenarios including Li-Fi, 5G-NR, VLP-aided systems, and the related applications in coordinated RANs. The concluding remarks are listed in the final section.

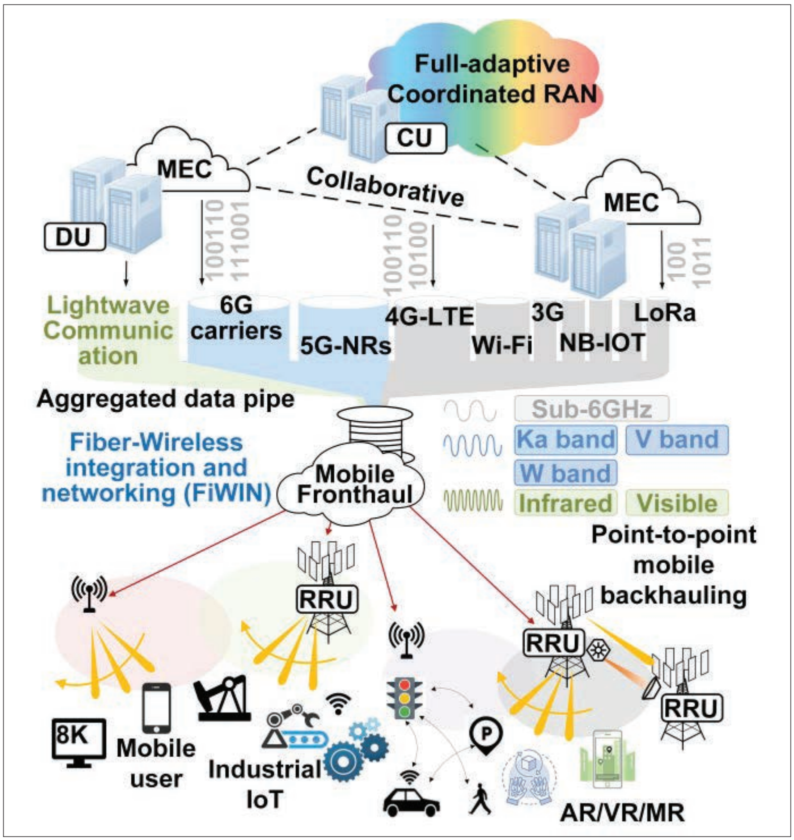

Figure 1. Fiber wireless integration and networking for the post-5G radio access network aggregating various available spectra.

Integrated Access and Outdoor Wireless NR-FSO Backhauling

Due to the ever-increasing user-specific data traffic, it has become more stringent for operating mobile backhauling/fronthauling, which relies on fiber links. Moreover, the capital expenditure (CAPEX), including the construction cost, site acquisition, and civil works, for deploying urgently needed new fiber infrastructure is getting prohibitive due to the geographical restrictions. Therefore, an alternative solution is desirable for delivering high-speed data transmission with rapid deployment.

As indicated in the previous section, the post-5G RAN cannot rely on a single RF-carrier band operation. Therefore, higher frequency bands such as mmWave and FSO have attracted lots of research interest. Fortunately, it is not an either/or choice for mmWave and FSO implementation. Both of them could provide complementary services for the existing wireless network and facilitate a smooth network migration. New opportunities are thus emerging for this kind of higher frequency band transmission, since they have abundantly available bandwidth for eMBB applications, fixed wireless access, and wireless backhauling.

On FSO, one of the OWC technologies, many research works have been done regrading to turbulence compensation, and receiver design such as diversity detection, coherent detection, and advanced DSP. In this section, we focus on the recent research progress in the FiWIN research center as shown in Fig. 3. Paired with DSP tech-

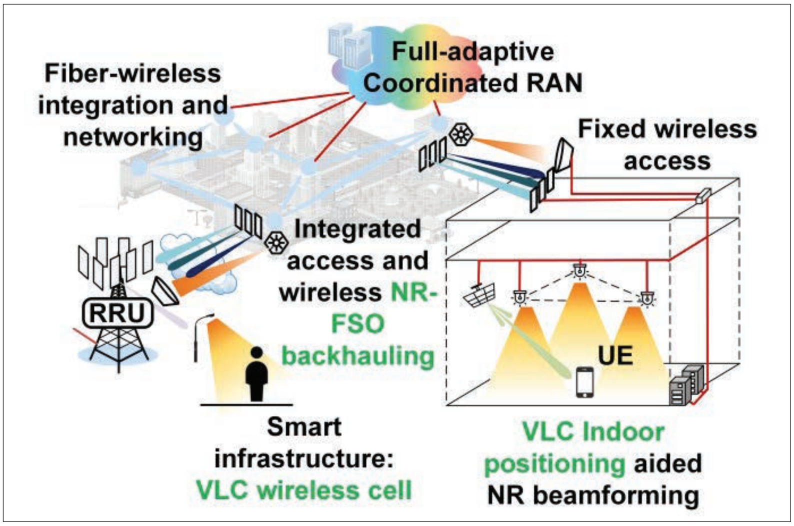

Figure 2. Conceptual diagram of photonic-aided fully adaptive coordinated RAN.

niques, the proposed system architectures can provide a high-speed data link and mitigate the impairments from weather turbulence. A field programmable gate array (FPGA)-based real-time system was also demonstrated in an integrated access network [6].

High-Speed OWC Transmission

For eMBB applications, FSO links can utilize a commercially available polarization modulator with a direct detection scheme. Since the polarization state of transmitted data is stable in free space, the identical signal with opposite sign could be modulated in two orthogonal polarizations at the transmitter side. After wireless transmission, the two polarized signals can be detected separately after the polarization demultiplexing at the receiver side. A subtraction operation is applied subsequently to mitigate the common mode noise. This is the first time that a 400 Gb/s PAM-4 FSO transmission through the polarization modulation and direct detection (PolM-DD) scheme is successfully demonstrated [7]. Four wavelengths, each carrying a 100 Gb/s PAM-4 signal, are aggregated in free space for data delivery. Compared to an intensity modulation and direct detection (IM-DD) system, the PolM-DD system performance is further improved. Moreover, the tolerance to the amplitude fluctuations attributable to weather turbulence is enhanced. The proposed PolM-DD scheme can be applied in the scenario of communication between objects with fixed positions (e.g., building-to-building communication, outdoor-to-indoor relay, or table-to-ceiling communication), where vibration is small and predictable. It offers a promising and flexible option to solve the ever-increasing requirement for large capacity with simple system implementation at an affordable cost.

mmWave-FSO Integrated Design for Weather Turbulence

It is challenging to deploy a pure FSO link in an outdoor environment, since it is sensitive to weather turbulence, line of sight (LoS) blocking, transmitter/receiver misalignment, and so on. Multi-relay FSO systems based on either a decode-and-forward or an amplify-and-forward scheme can mitigate the blocking impairment. Different beam tracking, acquisition, and pointing mechanisms [8] based on mechanical or electrical control could be employed to mitigate the misalignment and improve the mobility depending on the application scenarios. For the initial market of the 5G network (a.k.a., fixed wireless access), the mobility and misalignment issues can be effectively controlled because it operates in a relatively static wireless channel, and it allows a longer time for network initialization. In terms of bad weather conditions, combining mmWave and FSO complementarily in outdoor systems is a promising solution. FSO is easily degraded by fog and haze in the outdoor environment. However, mmWave is subject to a different weather condition (e.g., rain). Therefore, considering that FSO and mmWave are sensitive to different weather conditions, an ultra-reliable outdoor system that combines mmWave and FSO is proposed and demonstrated experimentally. The hardware/software switching or joint bit-interleaved coding to determine which channel to utilize based on the instantaneous channel state information can be deployed. However, these schemes induce high system complexity due to the requirement for a feedback loop. In this case, DSP techniques such as adaptive diversity combining technique (ADCT) [4] have been proposed, which can sense the signal quality adaptively and then assign weight according to the result from blind error vector magnitude (EVM) estimation. Theoretical analysis has proven that, by using the weight obtained from EVM, the combined system yields the optimal signal-to-noise ratio (SNR), and thus the optimal performance [5]. The weights of the two channels can be adjusted adaptively based on the channel conditions, and there is no need for a feedback switching loop. Experimental results have shown that the ADCT system improves system reliability under various weather conditions [4].

Burst Mode Interference Mitigation

In wireless systems, interference hunting is nontrivial, including interference sensing, avoiding, and cancellation. Mitigating interference without interrupting the existing service during the interference resolving period is a very important fiber-wireless networking technology for efficient mobile fronthaul access architecture. To further combat burst mode interference, repetition coding and a coordinated mapping and combining (CMC) [5] algorithm can be utilized in single-channel operation. A CMC algorithm is an upgraded algorithm from repetition coding. Figure 4 shows the principle of a CMC algorithm. At the transmitter side, the same data blocks are duplicated and mapped in both the frequency and time domains. The mapper ensures that the minimum spacing between the same data blocks is maximized by interleaving the duplicated blocks using even interleaving distances. The dispersive distribution makes the signal less susceptible to burst distortions since the signal is recoverable from other unaffected signals. Similar to the principle of ADCT, the weight is inversely proportional to the normalized square of EVM obtained from the blind EVM estimation, and it yields the optimal recovered signal. By using the CMC algorithm, the system reliability

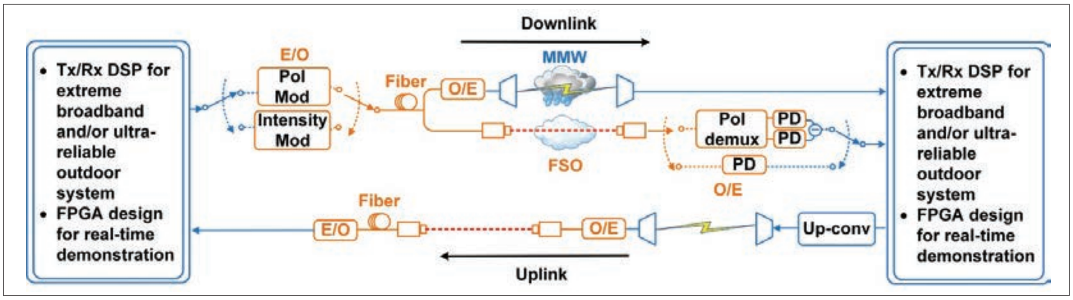

Figure 3. Integrated access links using NR-FSO and advanced DSP techniques for 6G fronthaul network. Pol: polarization; PD: photodetector.

and power margins are enhanced [5]. It is worth noting that this algorithm takes advantage of the abundant bandwidth of the FSO and mmWave system. In the case of fair channel conditions, the EVM floor is significantly reduced. Also, when the desired signal suffers from burst interference, the system can maintain a low EVM floor with a small penalty.

Therefore, the integrated NR-FSO system is an attractive solution in outdoor environments for providing post-5G or 6G ultra-reliable services under diverse weather conditions. Compared to the ADCT, the system power margin and reliability can be improved by adopting CMC algorithms. Thus, the choice depends on the required system performance, such as receiver sensitivity, bandwidth availability, interference tolerance, and DSP complexity.

Real-Time Implementation of NR-FSO Integration Links

The bidirectional NR-FSO link using real-time FPGA was demonstrated, and different user scenarios were investigated [6]. For a downlink hybrid mmWave-FSO system with 100 km fiber, targeting rural area applications, the FSO path has better stability (0.7 percent EVM variation) compared to the mmWave channel (1.7 percent EVM variation). Since the mmWave path has electrical amplifiers paired with horn antennas, it is less suspectable to the addition signal of FSO. On the other hand, with a simpler interface with paired collimators, the FSO channel is more sensitive to the addition mmWave signal and suffers from higher received power penalty. For the fiber-FSO-mmWave bidirectional link, the desired signal passes by each channel in sequence, and the impairments from the mmWave amplifier is more significant. The real-time FPGA demonstration verifies the required functionality and stability of seamless system integration and provides a proof of concept of the hybrid system operation. The breakthroughs in wireless NR-FSO in the FiWIN center are summarized in Table 1.

Integrated Indoor VLC and 5G-NR Beamforming

In post-5G access networks, one significant leap is led by network virtualization through intelligence management. In particular, the "one-size-fits-all" approach in 4G/LTE no longer works. Future RANs should have high flexibility to support diverse applications. In this case, in post-5G networks, it is unjustifiable that the "RFs-fits-all" approach is applied for proliferated wireless applications. In other words, function decoupling through an all-spectra coordinated RAN is imperative in conjunction with OWC. A field trial joint 5G-VLC network was demonstrated aiming to serve vehicle-to-everything (V2X) applications [9]. The end-to-end latency of environment sensing data and emergency alarm were studied.

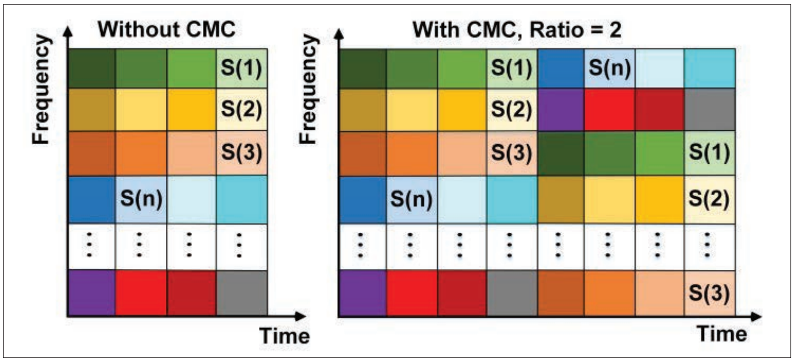

Figure 4. Principle of the coordinated mapping and combining (CMC) algorithm.

One of the key challenges in the post-5G network is the access operation in the indoor environment, which consumes most of the wireless data link capacity. By taking advantage of the existing LED illumination systems, an all-spectra coordinated RAN integrated with OWC ushers in a key indoor wireless application for providing complementary services by Li-Fi. Since Li-Fi operates at lightwave frequencies, it would not interrupt or cause interference to the existing wireless service delivery using low-RF or even 5G-NR. Moreover, the transmission distance of Li-Fi is relatively short, typically from the ceiling to the floor. The Li-Fi channel is more stable and exhibits a higher SNR for the high-speed downlink signal with an LoS method. In Li-Fi operation, LEDs could act as the optical femtocells [10], allowing multiple UEs to connect to the network simultaneously. There would be a trade-off between the uniform indoor illumination and the co-channel interference among LED devices. Nonetheless, this could be mitigated via the interference cancellation or the centralized management residing in the all-spectra coordinated RAN.

OWC Non-LoS Indoor Transmission

OWC systems are sensitive to the blocking obstacles in the LoS path and suffer from the SNR degradation in the non-LoS path. Therefore, it is nontrivial to make use of the coexistence of OWC and RF systems to provide effective solu-

	Data	Methods	Performance enhancement
F. Lu *OFC 2018*	OFDM & PAM	Repetition coding	Up to 3.2- dB ROP gain
R. Zhang, *J. Lightwave Tech.*	OFDM	CMC algorithm	Reliable with weather turbulence, up to 9-dB ROP gain
R. Zhang, *Photonic Tech. Lett.*	PAM4	PolM-DD	400-Gb/s under weather turbulence
Y. Alfadhli, *OFC 2019*	OFDM	FPGA	Real-time demonstration

Table 1. Comparison of integrated access and wireless NR-FSO backhauling/fronthauling.

tions [11]. FSO can act as the wireless relays and support higher bandwidth to seamlessly deliver signal in a fiber-FSO-mmWave link. Therefore, the non-LoS issue can be circumvented via multiple relays and pass by the UE mobility issue to the mmWave system. A non-LoS solution is to integrate a reconfigurable spatial light modulator with an FSO link. When there is a blocking obstacle, by controlling the wave front, the FSO beam can be steered toward the receiver after reflecting by a diffuse surface. The received SNR can be significantly enhanced via this optical beam steering method [12].

5G-NR Beamforming System

Besides exploring the OWC schemes, the 5G-NRs are also very important wireless resources in the all-spectra coordinated RAN. However, the wireless propagation loss becomes higher as the employed RF carrier frequency increases. The phased array antenna is the crucial device for compensating the link loss. Applying a phased array antenna will result in a narrow beam property, and thus makes beam management mandatory. The current mmWave beam management includes five steps, which are the beam alignment initialization, transmitter beam coarse-steering, beam index feedback, transmitter beam fine-steering, and receiver beam alignment. For instance, in the downstream direction, after initializing the beam alignment, the training sets are transmitted from the transmitter side in uniformly spaced directions and scan all the possible 3D positions to find out the UE location roughly. UE then determines the best connected beam direction by the training and sends the beam index back to the transmitter side. After the first round of the beam alignment, the same procedure would be conducted again with a finer spatial angle to further enhance the beamforming gain. This beam management method requires massive training sets, and it is time-consuming for finding the accurate UE location.

VLP Aided 5G-NR Beamforming System

Positioning is a new focus in 5G networks, as indicated in 3GPP Rel-16; hence, new reference signals are defined for downlink (DL) positioning with quadrature phase shift keying (QPSK) modulation. The positioning is not yet combined with beamforming systems, since the accuracy of the RF positioning is much larger than the 5G-NR antenna form size. In the indoor scenario, to simplify this procedure, a function decoupled all-spectra coordinated radio access network could facilitate the mmWave beam management through the visible light positioning (VLP) system, which achieves highly accurate positioning. The frequency and time resources for training sets in the current beam management procedure could be released, and the available RF resources could be utilized efficiently for data transmission. Meanwhile, since the proposed scheme operates with the lightwave frequency, it would not interrupt the existing RF wireless channels (e.g., low RF, LTE, Wi-Fi). With the help of the VLP system, the first step of the proposed beam alignment is initializing the positioning system. The UE location could be accurately estimated within a few centimeters. After locating the UE location, the transmitter and receiver could conduct the beamforming concurrently without sweeping the beam in all of the spatial directions.

Several indoor VLP systems have been reported recently [13–15]. Sensing data were encoded in the illumination light through LED systems and detected by the light sensors in off-the-shelf devices (e.g., smartphone and smart watch). The position of the mobile device could be estimated through the received signal strength (RSS), because it is positively related to the transmission distance. The indoor space could be evenly divided into multi-VLC cells for uniform illumination as well as broadening the cover range of the positioning system.

To obtain an accurate RSS, the receivers in VLP systems are mostly mounted parallel to the LED transmitters. However, the tilted receiver would result in a significant error, and the estimated UE location pattern would be bent. On the other hand, the interference among the sensing signals from dedicated LEDs would significantly degrade the positioning accuracy. To mitigate the inter-cell interference, time-division multiplexing could be applied. However, it requires lots of networking effort, which increases the network complexity. The LED transmitters in a single cell can operate at different RF frequencies to deliver the distinct identity (ID) sensing signals with minimized interference.

With the knowledge of the absolute locations of LEDs and RRUs, the angle of 5G-NR beamforming link could be acquired, which is exactly the necessary information for beam management.

AI Aided VLP for 5G-NR Beamforming

Artificial intelligence (AI) plays a major role in 5G and the following 6G wireless networks, starting from the device level to the networking level. Versatile applications are enabled by AI, such as medium access control (MAC)/physical layers optimization, flexible RAN configuration, zero-tough self-organization networking, and the VLP system. A weighted k-nearest neighbors model was applied to enhance the VLP accuracy using off-the-shelf devices [13]. The positioning error is 2.7 cm in a 2D space.

In our previous work [14], an artificial neural network (ANN) algorithm in cooperation with RSS was proposed to improve the positioning accuracy. The proposed machine learning method is capable of self-learning and self-configuration, which helps the beam tracking for moving objects. The indoor environment could be divided into multiple triangular cells, as shown in Fig. 5. The intra-cell interference could be mitigated through modulating the ID signals on the different RF carriers. After recovering the 50 kb/s ID signals, the UE location could be estimated through an ANN. An average positioning error of 3.6 cm with a height tolerance range of 15 cm were achieved. This work was further extended to cover a 3D positioning system [15]. To enable the VLP-aided mmWave beamforming for post-5G RAN, the indoor positioning system must be 3D, and the minimum location accuracy has met the physical size of the NR phased array antenna. For instance, for a 1 × 4 phased array antenna with half-wavelength spacing for conducting 60 GHz beamforming, the form size is around 1 cm ($\lambda/2 \times 4 = 1$ cm); thus, at least 1 cm positioning resolution is mandatory. To fulfill the above requirements, a two-layer ANN model was employed. In contrast to the single ANN layer, nine input nodes, two hidden layers with eight nodes and five nodes, respectively, and three output nodes were implemented in the two-layer ANN model. 50 kbaud QPSK signal was applied to carry the ID information. A world record of positioning resolution of 0.9 cm in a unit cell volume of 0.9 × 1 × 2.7 m^3 was demonstrated for a VLP aided NR beamforming system.

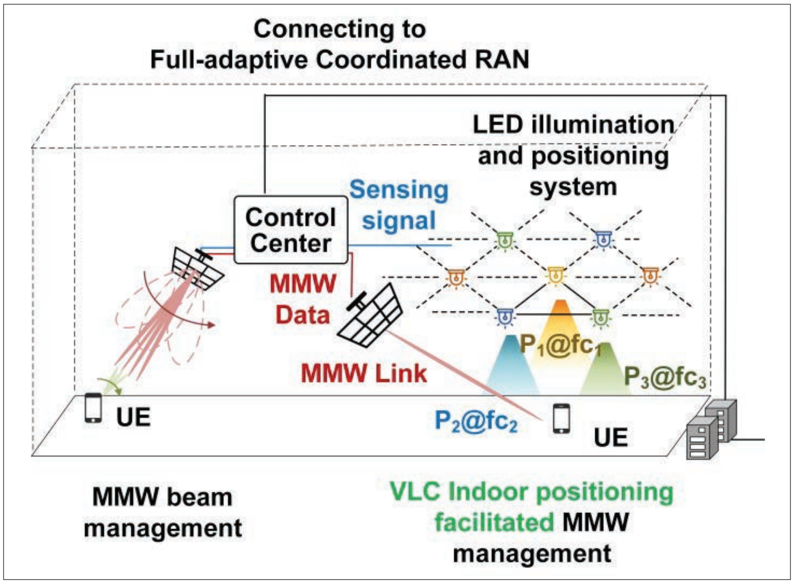

Figure 5. VLC indoor positioning aided NR beamforming via full-spectra function decoupling in post-5G coordinated RAN.

Research Opportunities

Implementation of All-Spectra Operation: 5G-NR integrated with a beamforming system was proposed; however, it is not widely adopted in the commercial network due to high system cost, increased complexity, as well as the complicated beam tracking and management issue discussed in the previous section. One potential research opportunity is to design an interface of VLP and NR systems to fully utilize the available hardware and resource for efficient wireless services delivery. A VLP system using smartphone embedded image sensors or camera may be an option.

Performance-Driven 6G RAN with MEC: As shown in Fig. 1, multi-access edge computing (MEC) located in CU/DU is merging with the RAN architecture. It plays an essential role as the interface between users and resources. Accordingly, AI-enabled network management could benefit the all-spectra coordinated RAN. Moreover, MEC leverages the distributed data and computing power designated to the service type and coverage. When data traffic is heavy, it needs to migrate the workload to other MECs. In this case, the FSO-mmWave integrated backhauling becomes an effective platform, providing ample research opportunities in the upcoming 6G network.

Advanced Waveforms and DSP Techniques: By taking full advantage of abundant frequency resources in FSO and/or 5G-NR links, advanced waveforms, such as orthogonal chirp division multiplexing (OCDM) or subcarrier spreading orthogonal frequency-division multiplexing (OFDM), are attractive solutions for mitigating burst mode interference. With the relatively stable wireless channel of higher frequency band, geometric shaping (GS) and probabilistic shaping (PS) can be applied for better channel utilization. Finally, due to the characteristics of LoS and narrow beamwidth, FSO and 5G-NR transmissions can enable spatial domain multiplexing and coordination to significantly increase the channel capacity and flexibility.

Conclusions

With ever-increasing data traffic demand of wireless applications, new and efficient system architectures for post-5G networks are emerging. A fully adaptive and coordinated RAN architecture is a key enabler to meet diverse system operation requirements and enrich the user experience. In this article, we emphasize function decoupling through incorporating all-spectra data transport techniques that include 5G-NR, FSO, and VLC. By considering physical properties of data-carrying channels, the all-spectra resource can be utilized efficiently to achieve greater performance in future communication networks. Discussions are partitioned into two sections: integrated access of wireless NR-FSO backhauling and indoor communication systems via 5G-NR, VLC, and VLP aided NR beamforming. In the former scenario, the high-speed FSO link is supported via a novel PolM-DD scheme. The integrated FSO-NR systems with advanced DSP are investigated to mitigate the burst interference and overcome diverse weather conditions. The feasibility of a seamlessly integrated fiber-FSO-mmWave system was demonstrated via a real-time FPGA-based software defined radio testbed.

Nowadays, indoor communication consumes most wireless data link capacity. OWC operated with LoS and/or non-LoS transmission can support complementary services without interrupting the existing RF channels. The current beamforming management scheme of 5G-NR would demand valuable physical layer resources as well as an elaborate network control protocol. Aided by the existing VLC illumination system, part of the functions for the beam management process can be addressed by the VLP system. The 3D positioning system with < 1 cm accuracy can satisfy the strict demand for NR beamforming operation assisted by AI techniques. To achieve a smooth and seamless transition to the post-5G function-rich network platform, the FiWIN center has demonstrated a fully adaptive, all-spectra coordinated RAN with function decoupling. Research opportunities aligned with 6G networks to deliver diverse user-specific data services are forecasted and discussed.

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