Wired and wireless seamless networks by photonics

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Abstract
Demand for wireless services is increasing rapidly, due to deep penetration of mobile terminals, such as smartphones. Radio spectrum congestion is an important issue, even for conventional mobile services. One of the possible solutions would be to use wired and wireless seamless networks consisting of radio and optical links, where huge data traffic can be offloaded from radio-waves in the air to optical signals over fibres. This paper provides seamless network configurations which can be applied to 90-GHz high-speed wireless links and high-resolution radars. We focus on applications for public transportation systems including airport runways, railways, etc.

1. Introduction

Radio communications can provide agile deployment capability, and flexibility for end-users. However, it is rather difficult to achieve long-haul or large capacity data links by radio-waves, because of the limitations of radio-wave spectrum resources, especially in microwave bands whose frequency is lower than 30 GHz. High-frequency carriers such as millimeter-wave (30–300 GHz) and THz wave (0.1–10 THz), where a wide range of spectrum is available for mobile services, are expected to offer over 100 Gb s\(^{-1}\) transmission for future mobile services such as beyond 5G [1, 2]. However, transmission distance would be shorter than a few kilometers, due to large propagation loss in such high-frequency bands, so that a number of base stations (BSs) are needed for high-speed wireless services with wide coverage. The number of required BSs would be much larger than the number of users, i.e. equivalent to the entire population of human beings on Earth [3].

Networks connecting BSs should have many interfaces between wired and wireless links. Thus, cost and power consumption of such in the interfaces would have a significant impact on CAPEX (capital expenditure) and OPEX (operation expense) of mobile network systems including wired links between BSs. Also, the reduction of latency at the interface is significant to provide low-latency connectivity for mission-critical applications. Media converters bridging wired and wireless links should have a very simple configuration to reduce power consumption and cost, as well as latency [3, 4]. Radio and optical links would be seamlessly connected through the media converters. The seamless access networks consisting of radio and optical links would provide high-performance data transmission with the flexibility for end-users, where media converters make connections between radio and optical signals [5–7].

Radio-over-fibre (RoF) which can transfer waveforms for radio services over optical fibres would be useful to provide media converters for radio-waves in the air and optical signals in the fibres, where photonics can offer radio signal generation and detection [8]. As shown in figure 1, a RoF system transmits radio-waves over optical transmission links consisting of electro-optic conversion devices and photodetectors. Loss of single-mode optical fibres is smaller than \(0.2 \text{ dB km}^{-1}\) at 1550 nm. On the other hand, loss of conventional signal distribution systems using metallic cables or waveguides would be very large for high-frequency signals, while that of RoF systems is almost constant. Transmission loss is negligible in RoF systems whose transmission distance is shorter than 10 km. The total loss of the systems largely depends on the efficiency of electric-to-optic and optic-to-electric conversion devices.

A number of links would be required to provide two-dimensional wide-area coverage by RoF. On the other hand, for one-dimensional service coverage, we can construct RoF systems with a moderate number of antenna...
units located along with optical fibres to form linear shape coverage for important public infrastructure such as motorways, airport runways, railways, etc. Millimetre-wave systems with linear shape coverages formed by linearly located remote antenna units, are called 'linear cell'. High-speed wireless communication systems can be constructed by this linear cell system, which is controlled by the use of train location information. The linear cell can be applied to high-resolution radar imaging for runway surveillance.

Here, we focus on the requirements and features of short-distance and huge-capacity radio-wave transmission systems. Millimetre-wave and THz wave can offer over 100 Gb s$^{-1}$ wireless transmission through the use of wide spectrum. We can mitigate the congestion by increasing the spectral efficiency (SE) of radio signals. Another option would be to use high-frequency bands where congestion is not so severe as of now. Impact on congestion mitigation can be comprehensively measured by a product of carrier frequency and spectral efficiency, (CFSE: carrier frequency spectral efficiency product, henceforth) [8].

The CFSE of millimetre-wave and THz-wave radio systems reported in recently reported papers [9–37], are shown in figures 2 and 3 with respect to carrier frequency (CF) and data rate. Advanced modulation formats such as quadrature amplitude modulation (QAM) provides large SE. High-speed wireless systems shown in figure 2 use various types of modulation formats, including amplitude shift keying (ASK), quadrature phase shift keying (QPSK), 16QAM and 64QAM, realize large CFSE. Precise waveform control is rather difficult in the high-frequency region so that complicated modulation formats such as 16QAM and 64QAM could not be applied to high baud rate systems. This is the reason why the CFSE decreases when the data rate is larger than 100 Gb s$^{-1}$. Figure 3 shows the CFSE as a function of CF which has a maximum around 300 GHz. That implies that waveform control and signal processing used in THz bands above 300 GHz are not matured enough for advanced modulation formats.

These results indicate that the status of the state-of-art wireless technologies can be described by the CFSE which shows a contribution to the mitigation of spectral congestion. For example, from figures 2 and 3, we can
conclude that high-speed THz communications can be achieved in a frequency range lower than 300 GHz without losing spectral efficiency, while the bit rate would be up to 100 Gb s\(^{-1}\).

2. Wired networks for radio services

Modern mobile networks, such as LTE, can provide broadband data connection services, through base BSs. Roles of wired networks are very important in such mobile networks to provide worldwide coverage with limited available radio spectrum resources, where mobile backhaul (MBH) and mobile fronthaul (MFH) connect BSs, as shown in figure 4 [38, 39]. The BSs have baseband units (BBU) connecting radio-wave and baseband signals, as well as remote antenna units (RAUs) for radio-wave emission and reception.

The MBH connects BBUs for data transfer from and to BSs. Requirements for the MBH would be similar to that of general digital data transfer networks. On the other hand, the MFH makes links between BBUs and RAUs to provide transfer of waveforms for radio services. RAUs connected to BBUs can offer many small cells for broadband services. Many RAUs can be controlled by a BBU or a BBU pool. Configuration of RAUs can be very simple because complicated signal processing function can be offered by the BBUs. In modern mobile networks, digital optical transmission links are commonly used for waveform transfer. Such links are called digital RoF (D-RoF), where waveforms are described by digitized numbers [40]. Low-cost optical digital transmission systems can be applied to the MFH for 3G and 4G systems because the bandwidth requirement would be smaller than 10 Gb s\(^{-1}\). In the early stages of mobile system development, analogue RoF (A-RoF) was used for MFH applications underground or in tunnels, because high-speed digital transmission had not been matured yet [41].

Device and systems using 28 GHz have been developed to offer high-speed data transmission services whose wireless interfaces faster than 10 Gb s\(^{-1}\). Larger transmission capacity would be required in beyond 5G or 6G systems, because demand for wireless networks has experienced continuous growth. In high-bands, cell sizes should be small because of large propagation loss of millimetre-waves. Thus, we should rely on many RAUs connected by seamless networks consisting of A-RoF and D-RoF.

5G mobile networks would offer super broadband data transmission with low latency and high reliability, for various applications including the Internet of Things (IoT), which enables connected devices to collect and exchange data [11]. Particular cases in agriculture or forestry require wide-coverage in unpopulated areas. However, for example, the ratio of mobile service coverage area to the total territory of Japan would be approximately 60% [3], while almost 100% coverage of services is provided in central business districts, residential areas, areas along highways, etc.

It would be rather difficult to increase transmission capacity by the use of the low bands, because the available bandwidths are not wide enough to provide high-speed wireless transmission. The high bands should be used to offer broadband wireless service. Due to transmission distance limitation in the high bands, beyond 5G or 6G mobile systems need many small cells, e.g., femto- or picocells, to achieve large service coverage.

Legacy optical fibres are commonly used as transmission media to connect the BSs in existing mobile networks. However, it would be rather difficult to make connections to many BSs in beyond 5G or 6G networks, only by the use of fibres, because the number of BSs would be much larger than in conventional networks. High-speed wireless links can be used for connecting BSs, as well as for links between BSs and mobile terminals. A number of low-cost and high-performance interfaces between wired and wireless links would be required in future mobile networks [3, 4, 41].

In conventional optical fibre communication systems, enhancement of spectral efficiency was thought not to be so important that simple modulation formats, such as on-off-keying (OOK), are commonly used for data transmission. It was rather difficult to obtain precise waveform control which is required for complicated
modulation formats. Optical fibre transmission bandwidth is much wider than bandwidth of conventional coaxial cables.

However, in modern optical fibre systems with wavelength-domain-multiplexing (WDM), almost all the available optical spectrum has been already used for multi-channel transmission. Recently, optical fibre systems with advanced modulation formats including QPSK and QAM have achieved large spectral efficiency [6], where digital coherent technology offers vector modulation and demodulation. Optical phase fluctuation and chromatic dispersion with optical signal propagation over fibres can be compensated by digital signal processing (DSP) at optical signal receivers.

The same scenario would happen in millimetre-wave and THz-wave bands where radio spectrum congestion is not so high as of this moment. We should increase spectral efficiency of radio-wave signals even in millimetre-wave and THz-wave bands by using the advanced modulation formats with vector optical modulation, coherent signal detection, and digital signal processing.

Recently, space-domain-multiplexing (SDM) with multi-mode or multi-core fibres has been developed to achieve over Pb/s optical transmission, where data rate per one WDM or SDM channel would be up to 400 Gb s⁻¹. By using multi-level modulation formats such as QPSK, 16-QAM, bandwidths of signals generated by one transmitter can be up to a few hundred GHz.

Fractional bandwidth of the signal with respect to the carrier frequency of THz communication systems would be smaller than a few tens of percent, which would be feasible to design filters and other components required for the radio systems. That implies that the requirement for IF or baseband signal processing functions in THz transmitters and receivers would be similar to that of optical transmission. Devices and signal processing developed for optical fibre communications can be applied to THz communication systems. On the other hand, the high-speed radio-wave links whose capacity is close to that of optical fibre links would be valuable for optical fibre backups to mitigate a possible surge of traffic demands during disaster recovery activities.

DSP-based digital coherent systems can compensate signal deformation in radio-wave links over as well as in optical fibres [41]. RoF links transmit waveforms for radio-wave links on intensity profiles of lightwaves over fibres, by using high-speed electro-optic devices such as modulators and photodetectors. A combination of millimetre-wave RoF and digital coherent can provide wired and wireless seamless links whose bit rate would be close to 100 Gb s⁻¹ [3]. Reduction of cost and power consumption at media converters connecting wired and wireless links would be very important to enhance total performance of the seamless networks.

Latency reduction in data transmission is also one of the important issues for particular applications such as data transfer for high-frequency trading and online gaming. Recently, low-latency transmission by radio-wave in the air has been investigated, to utilize the radio-wave propagation speed in the air, although data rate would be smaller than in optical fibre links. The propagation speed in the air is much faster than in the fibres. Wireless and wired seamless links would be useful to mitigate such demands both for high capacity and low latency. RoF-based transparent waveform transfer would provide low latency media conversion between optical and radio-wave signals [42].

3. Configuration of seamless links [41]

Figure 5 shows a configuration of seamless access networks with conventional media converters bridging radio and optical links. At a media converter consisting of an optical receiver (Rx) and a radio transmitter (Tx), the optical signal is detected and converted into a radio signal. At the other media converter with a radio Rx and an optical Tx, the RF signal is demodulated and converted into an optical signal again. When RF transmission uses coherent signal detection for multi-level modulation formats such as QAM, the converters should have DSP...
units, as shown in figure 6. Multi-level modulation formats became popular in optical communications. If we use such modulation formats also for optical links, the media converters should have many DSP units as shown in figure 6. Latency and power consumption in the converters would be an issue for mission-critical applications. On the other hand, latency in optical-to-electric (O/E) and electric-to-optical (E/O) conversion is only from signal propagation delay in the devices, so that it would be negligibly smaller than that in DSP.

As shown in figure 7, RoF can offer a simple configuration for bridging optical and radio signals, where the number of required DSP units would be minimized. Waveforms pass through the media converters without any signal processing, while the DSP unit at the receiver comprehensively compensates waveform deformation in optical fibres and radio wave propagation in the air. At the RoF Tx, a waveform generated by the DSP is converted into an optical signal by the E/O conversion device. A photonic local oscillator generates an optical spectral component whose frequency difference from the E/O converted signal is corresponding to the carrier frequency of the radio-wave. Frequency and phase stability of photonic oscillator signals would have an impact on the performance of radio links.

RoF provides low-latency signal conversion because the latency consists of propagation delay in conversion devices. The total latency of optical and radio links including media conversion would be much smaller than in conventional systems with media converters with many DSP units. Wireless links would offer lower latency than in optical fibre communications, because of the difference in refractive indices in optical fibres and the air [42]. In general, the transmission capacity of wireless links is much smaller than in optical fibre communications. Thus, it would not be feasible to use wireless links to reduce the latency. On the other hand, THz communications can be used for low-latency links, because the difference of bitrates in wireless and wired are small between THz and optical systems. Link distances of THz radio systems cannot be longer than a few kilometres, so that we should use seamless links, where latency in links with radio-wave would be reduced by a factor of 1/1.5 with respect to optical fibre links.

In RoF based systems, E/O and O/E devices should respond to the carrier frequency of the radio-wave. It would be rather difficult to have direct E/O or O/E conversion in high-frequency bands over 100 GHz. For THz systems, as shown in figure 8 IF-over-fibre (IFoF) would be feasible to provide wired and wireless seamless links.
THz carrier components are generated in the radio FE in the media converter, through the use of a frequency multiplier.

Stable photonic local oscillator signals can be generated by using optical external modulators. A reciprocating optical modulator consisting of a phase modulator and two optical filters can enhance high-order harmonic components. An optical fibre loop with a single sideband modulator can generate high-frequency components up to a few hundred GHz. The photonic local oscillator signal can be distributed over fibres, to share the external modulator with many signal converters. Thus, we can reduce the total cost of the system without losing stability or purity of the radio signals.

To construct low-cost signal converters, robustness and small footprint are key issues for implementation. Semiconductor-based optical devices are promising in this scenario. Monolithic integration with electrical devices is also possible using semiconductors. Semiconductor quantum dots (QDs) are promising materials for high-performance photonic devices such as laser diodes, modulators, photodetectors and optical amplifiers from the viewpoints of ultra-fast response and wide wavelength range operation. In addition, QD devices would provide athermal operation where energy consumption will be reduced further.

4. Train communication network [44]

One of the important functions of mobile networks is collection of user location information by handshake or handover procedures between BSs and terminals. In general, the mobile networks cannot have information on where the terminals will be. Mobile terminals for many passengers in a high-speed train should have many simultaneous handover processes where the train arrives. Overall throughput will be very low because when the overhead due to handover is large. Linear cell systems can solve this issue by dynamically activating the cell where the train comes [4].

For train communication systems, we can use conventional wireless communication technologies such as LTE and Wi-MAX [45]; however, the capacity of the link is relatively small. Millimetre-wave radio transmission technology is sufficiently reliable for critical applications, such as train control. For example, the Maglev in China has been operated safely by millimetre-wave radio [46]. Figure 9 shows a linear cell train communication network (TCN), where node base stations (NBSs) are connected to a control station through an optical network. Optical carrier stations (OCSs) aggregate and distribute signals to NBSs which generate RoF signals for track-side radio access units (TS-RAUs) placed along railway tracks. Each TS-RAU is assigned to a different WDM channel, to form a logical point-to-point connection with an NBS with a physical passive single-star implementation.

Signal flows in the network connecting the NBS and TS-RAUs can be controlled by the use of train location information (TLI), managed by an operation direction centre (ODC), in order to activate the TS-RAU close to the train. A moving cell formed by the TS-RAUs follows the location of the train, so that the NBS can maintain the wireless link between the NBS and the transmitter on the train through the TS-RAUs, without complicated handover procedures. Dynamic routing function of RoF signals can be easily realized by using WDM channel selection devices, such as reconfigurable optical add-drop-multiplexer (RODAM). By using IFOF, we can reduce the required bandwidths of opto-electric devices in the NBSs and TS-RAUs, where the frequency can be converted into the desired millimetre-wave band at the TS-RAU.
Recently, various types of high-resolution imaging systems have been proposed for foreign-object-debris detection (FODD), which is an important function to ensure safe airport operation. A linear cell radar system consisting of many radar heads connected through an optical network can provide a few centimetres range resolution in linear shape areas whose lengths are a few kilometres [3].

As with wireless sensor network (WSN), the optical network in the linear cell system is dedicated for gathering information through sensors. In the linear cell radar system, the network would carry waveform generated at the radar heads to compile information from radar heads coherently at central signal processing units as shown in figure 10. The linear cell radar is an example of sensor-over-fibre (SoF) systems, which consist of many sensor heads connected by optical fibres to collect waveforms from the objects. The configuration of SoF is shown in figure 11. Joint signal processing offers high-resolution and agile imaging. In general, WSN transmits digital information digitized at each sensor in the same way as in MBH. On the other hand, SoF transfers waveforms as with MFH.

5. Linear cell radar [44, 47, 48]

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A linear cell radar system dedicated for runway surveillance has been reported recently in [47]. Four radar heads are located to monitor a landing area of a runway in Narita International airport. The distance from the radar heads and a central unit placed in the terminal area is shorter than 7 km. The dispersion effect in optical fibre transmission can be successfully mitigated by using carrier suppressed dual sideband optical modulation where a Mach-Zehnder modulator generates optical two-tone signals [8]. Frequency separation of the two spectral components in the two-tone signals would be swept rapidly for FM-CW signal generation. At the radar head, the optical signal is converted to W-band millimetre-wave signals by photodetectors, frequency multipliers and amplifiers. The sweep range and centre frequency of generated W-band FM-CW signals are 7.9 GHz and 96 GHz, respectively. Theoretical range resolution, which is given by \( \frac{c}{f_{BW}} \) (\( c \): the speed of light, and \( f_{BW} \): the occupied bandwidth of the chirp signal.), \( \Delta R \) would be 1.9 cm. Metal objects whose radar cross-section is larger than \(-20\) dBsm can be detected within a distance of 460 m [47, 48]. Figure 12 shows an example of radar images obtained by one of radar units in the linear cell radar system. This is measured under light rain, so that the radar detected reflected waves from splashes by an airplane on the runway, as well as that from runway edge lights.

6. Conclusion

This paper reviewed wired and wireless seamless networks where RoF carries radio waveforms over fibres. We focused on applications in public transportation infrastructure. Combination of millimetre-wave RoF and digital coherent would provide high-speed access networks or high-performance sensing systems where radio-wave forms are coherently processed in central units. External modulation for high-order sidebands and precise lightwave control would be indispensable for stable local oscillator signal generation, and RoF signal synthesization. QD devices would provide low-cost signal conversion with athermal operation.

The linear cell, which is one of the wired and wireless seamless networks, can provide linearly shaped coverage by RAUs located along optical fibres. Such systems would provide low latency and high-speed wireless links in millimetre-wave or THz bands. High-speed handover-free transmission dedicated for high-speed trains can be achieved by using a linear cell system where signal flows in optical networks are controlled by train location information. The linear cell configuration can be also applied to high-resolution imaging. The wired and wireless seamless networks including the linear cell can provide large capacity transmission and high-resolution imaging with limited radio frequency resources. Latency in A-RoF systems would be smaller than in conventional systems based on digital signal transmission.

A Linear cell system forms a one-dimensional linearly shaped coverage for public transportation. The number of required RAUs is proportional to the size of the coverage. On the other hand, a number of RAUs are required for beyond 5G or 6G applications where two-dimensional wide coverage is needed. Thus, the cost of the RAUs should be much lower than in linear cell systems. At the early stage of the RoF or IFoF system development, we can focus on applications in important public infrastructure such as airports and high-speed railways, where high-performance imaging or high-speed transmission is required. Through the deployment of the linear cell systems, we can expect realization of low-cost devices for future two-dimensional applications.

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