Review Article

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Low-power consumption seamless wireless and wired links using transparent waveform transfer

Abstract: This paper describes wired and wireless seamless networks consisting of radiowave and optical fiber links. Digital coherent technology developed for high-speed optical fiber transmission can mitigate signal deformation in radiowave links in the air as well as in optical fibers. Radio-over-fiber (RoF) technique, which transmits radio waveforms on intensity envelops of optical signals, can provide direct waveform transfer between optical and radio signals by using optical-to-electric or electric-to-optical conversion devices. Combination of RoF in millimeter-wave bands and digital coherent with high-performance digital signal processing (DSP) can provide wired and wireless seamless links where bit rate of wireless links would be close to 100 Gb/s. Millimeter-wave transmission distance would be shorter than a few kilometers due to large atmospheric attenuation, so that many moderate distance wireless links, which are seamlessly connected to optical fiber networks should be required to provide high-speed mobile-capable networks. In such systems, reduction of power consumption at media converters connecting wired and wireless links would be very important to pursue both low-power consumption and large capacity.

Keywords: millimeter wave; optical fiber; seamless.

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1 Introduction

Demands for wireless communications are expanding rapidly because of their flexibility, agile deployment capability, etc., though power consumption per bit/s in optical fiber transmission is much smaller than in radiowave wireless communications [1]. Radiowave wireless communication technologies are indispensable for mobile systems, to connect end users to networks. Fixed wireless systems also play important roles in core or metro networks especially in rural areas. However, it is rather difficult to obtain large capacity radiowave links, due to limitation of radiowave frequency resources especially in microwave bands. Millimeter-wave links can provide multi-Gb/s high-speed transmission; however, the transmission distance is limited by atmospheric attenuation. Thus, we should rely on optical fiber links to provide over high-speed and low-power consumption transmission. Hybrid network radiowave and optical fiber links would be useful to pursue user accessibility, large-capacity and low-power consumption data transmission services.

This paper describes wired and wireless seamless networks consisting of radiowave and optical fiber links. Digital coherent technology developed for high-speed optical fiber transmission can mitigate signal deformation in radiowave links in the air as well as in optical fibers [2]. Radio-over-fiber (RoF) technique, which transmits radio waveforms on intensity envelops of optical signals, can provide direct waveform transfer between optical and radio signals by using optical-to-electric or electric-to-optical conversion devices. Combination of RoF in millimeter-wave bands and digital coherent with high-performance digital signal processing (DSP) can provide wired and wireless seamless links where bit rate of wireless links would be close to 100 Gb/s [3]. Millimeter-wave transmission distance would be shorter than a few kilometers due to large atmospheric attenuation, so that many moderate distance wireless links, which are seamlessly connected to optical fiber networks, should be required to provide high-speed mobile capable networks. In such systems, reduction of power consumption at media converters connecting wired and wireless links would be very important to pursue both low-power consumption and large capacity.

We will also discuss latency in radio and optical links. Reduction of latency in transmission is one of important issues for particular applications such as data transfer for high-frequency trading [4, 5]. Recently, wireless links has been paid attention to achieve low-latency transmission, where data rate would be much smaller than in optical fiber communications, but wave propagation speed is much higher in the air. Seamless wireless and wired 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 radiowave signals.

2 Power consumption of high-speed wireless systems [5]

Radiowave wireless systems can provide accessible and flexible broadband services, while power consumption per transmission capacity is much larger than in optical fiber communication systems. Some short distance wireless systems, such as Bluetooth, Zigbee, etc., are dedicated to low-power consumption data links; however, they are not designed for broadband services. Figure 1 shows power consumption per bit in short distance wireless systems [5].

That implies high-speed transmission links would be useful to reduce power consumption at radio transmitters. In principle, power consumption per bit would be independent from bitrate if the signal-to-noise ratio is constant. However, the transmitters should have components or functions, which are not directly connected to radiowave transmitters or receivers. Power consumption for some particular functions such as packet buffering, baseband signal processing would be proportional to time duration for transmission. High-bitrate transmission can reduce the duration largely. We deduce that this is one of the reasons why required energy per bit is small in high-bitrate systems.

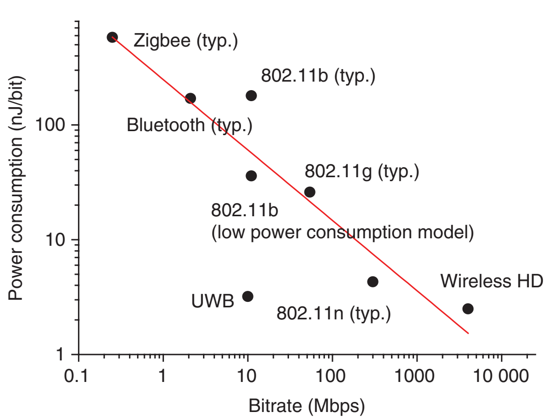

Figure 1 Bitrate and power consumption of short distance wireless data transmitters [5].

3 Telecommunication in millimeter-wave bands

High-speed radio links would require wide frequency bands. While it is rather difficult to reserve such bands in microwave regions, wide radiowave bands are available in millimeter-wave bands, in V-band (50–75 GHz), E-band (60–90 GHz), and W-band (75–110 GHz). Unlicensed bands in 60 GHz attract much attention for high-speed short distance telecommunications. However, 60 GHz bands are not suitable for moderate or long distance links due to large oxygen attenuation. On the other hand, in the range from 70 GHz to 110 GHz (E- and W-bands), atmospheric attenuation of millimeter waves is much smaller than in 60-GHz bands, as shown in Figure 2. Attenuation in dry air is the lowest at 94 GHz in the frequency region higher than 60 GHz. In this range, 71–76 GHz, 81–-86 GHz, 92–94 GHz, 94.1–100 GHz, and 102–109.5 GHz are internationally allocated for fixed or mobile radio services (95–100 GHz is only for mobile services in USA), as shown in Figure 3. In total, 25.4-GHz wide frequency bands can be used for moderate distance wireless telecommunication services in Europe and Japan, where over 100 Gb/s wireless links can be constructed with a modulation format with spectral efficiency larger than 3.94 bit/s/Hz.

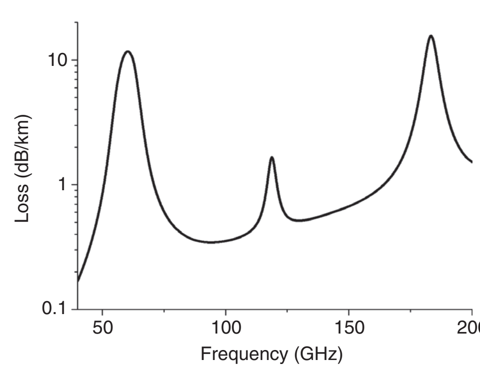

Figure 2 Atmospheric attenuation of millimeter wave [6].

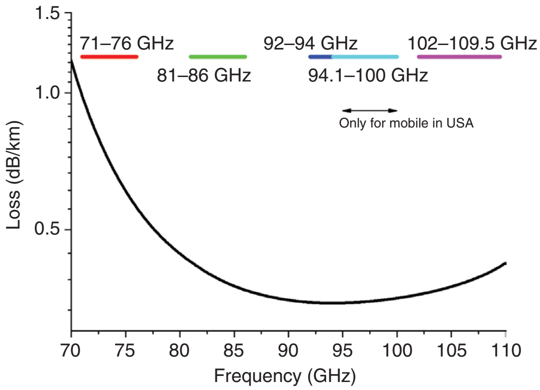

Figure 3 Atmospheric attenuation and spectrum allocated for telecommunications in millimeter-wave bands of 70–110 GHz.

4 Photonic-assisted high-speed millimeter-wave links

Even though available frequency spectrum is wider in millimeter wave than in microwave bands, multilevel modulation formats would be required for high-speed links. However, it is rather difficult to generate and detect such signals in high-frequency region by the use of electric devices, due to bandwidth limitation of electric circuits.

On the other hand, photonic devices can handle broadband signals easily. For example, simple optical couplers can split photonic signals with very high-frequency components. Simple modulation formats, such as on-off-keying (OOK) or differential phase-shift-keying (DPSK) were often used in commercial optical fiber communication systems because it was very difficult to control lightwave precisely without losing speed of modulation. The most important issue was to increase the modulation and demodulation speed, while required preciseness of signal generation and detection was not so high. For example, on-off extinction ratio (ER) of 20 dB is large enough for such modulation formats, though precise signal control is very important in radiowave wireless systems to follow radio regulations.

However, recently, precise lightwave modulation and demodulation technique has been developed for various advanced modulation formats including quadrature phase-shift-keying (QPSK), quadrature amplitude modulation (QAM), etc., to obtain enhanced spectral efficiency or receiver sensitivity in optical fiber transmission [7]. Arbitrary waveform can be generated by using vector modulation devices, which can control in-phase (I) and quadrature (Q) components independently. A dual parallel Mach-Zehnder modulator (DPMZM) consisting of two integrated Mach-Zehnder interferometer-based amplitude modulators can provide high-speed optical vector modulation, as well as analog modulation for applications such as single sideband modulation, chirp signal generation, etc. Precise amplitude modulation is required for more advanced modulation formats including 64QAM and 256QAM where eight-level and 16-level amplitude modulation is, respectively, needed in both I and Q components. Active trimming technique can increase the ER up to 70 dB [7]. High ER optical modulation has been used for generation of optical two-tone signals, which can be applied to photonic reference signals in array antenna systems for radio astronomy [8], high-performance photodetector measurement techniques [9], etc.

For receiving advanced modulation format signals, digital coherent systems have been developed for high-speed optical fiber transmission by the use of high-performance digital signal processors (DSPs), which estimate optical phase of the signal and mitigate waveform degradation in signal propagation. Conventional optical modulation and demodulation technologies can provide high-speed transmission whose baud rate is much higher than in radiowave systems. On the other hand, electric device-based radiowave wireless systems can control waveforms much more precisely than in conventional optical transmission systems. However, recently developed optical vector modulation and digital coherent techniques provide high-speed and precise lightwave control, which can be applied to radiowave generation and detection. As shown in Figure 4, an optical modulator generates a lightwave signal whose intensity profile is proportional to a waveform of a radiowave. At an antenna unit, the radiowave is converted from the lightwave by a high-speed photodetector. This technique is called radio-over-fiber (RoF). Over 10 Gb/s millimeter-wave transmissions hav been demonstrated recently [2, 3]. Figure 5 shows an experimental setup for 40 Gb/s millimeter-wave wireless transmission, where a carrier component in W-band was generated by two-tone optical signal generation with high-ER modulation technique described above [10].

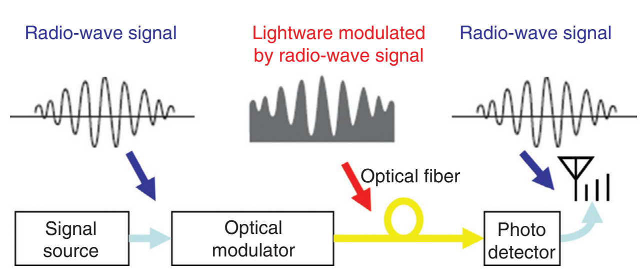

Figure 4 RoF system.

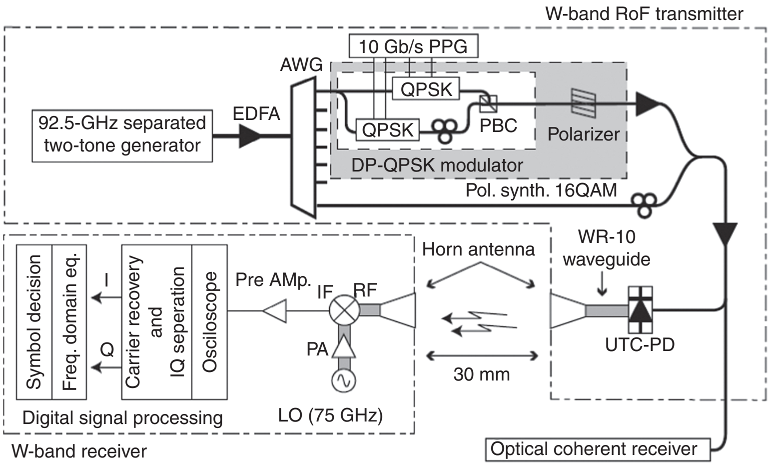

Figure 5 Setup for 40 Gb/s millimeter-wave transmission [10].

16QAM signal was optically synthesized by the use of two DPMZMs. The two modulators act as a photonic digital-to-analog converter.

5 Wired and wireless seamless links [11]

Figure 6 shows a schematic of a wired and wireless seamless transmission system consisting of a digital coherent-based optical fiber link and of a millimeter-wave wireless link. Wireless-to-wired or wired-to-wireless media converters (WWMCs) convert optical signals into millimeter-wave signals and/or millimeter signals into optical signals. The wireless link can be used as a backup, when the wired link is broken through an optical fiber cut. RoF can transmit optical signals with waveforms over optical fibers. 'Seamless' means that waveforms on optical signals in fibers can be transparently converted into millimeter waves at WWMCs, without using complicated digital signal processing. A WWMC comprising an optical-to-electric (O/E) converter and a radio front end (FE), can act as an optical-to-radio (O/R) converter, while a radio-to-optical (R/O) converter also can be constructed by a radio FE and an electric-to-optical (E/O) converter, as shown in Figure 7. A high-speed O/E converter or photodetector in the WWMC seamlessly transforms high-speed optical signals from a RoF transmitter (Tx) directly into radio signals.

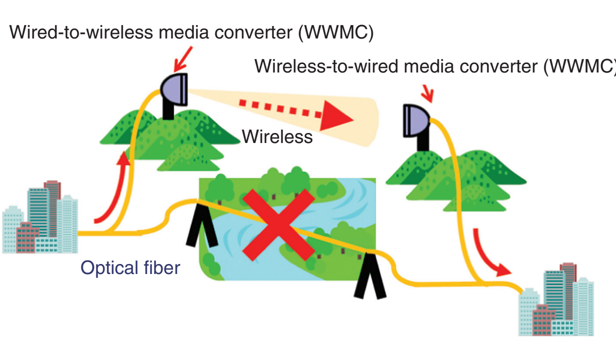

Figure 6 Wired and wireless seamless links.

On the other hand, the use of optical digital coherent detection techniques at the receiver (Rx) can completely compensate for transmission impairments such as media dispersion, eliminating the need to use a DSP altogether. Figure 8 shows a schematic of a combination of wired and wirelesss connection based on conventional media converters and digital optical transmission links, where WWMCs should have digital-to-analog/analog-to-digital converters and DSPs. We need more DSPs for advanced modulation formats in optical links. On the other hand, those in seamless links shown in Figure 7 would provide simple configurations and reduce power consumption in signal processing. WWMCs transfer waveforms from lightwaves to radiowaves or from lightwaves to radiowaves, where signal degradation would be accumulated. However, the DSPs in optical transmitter or receivers can mitigate the degradation comprehensively. As described above, E or W-band millimeter-wave bands are suitable for high-speed radiowave links, where attenuation of millimeter waves in dry air tends to be <1 dB/km. However, the attenuation increases largely under heavy rain conditions. Free space optic (FSO) links would be also useful as backups of wireless links, when the visibility is larger than a few kilometers. FSO link performance would be degraded largely due to fog or smoke [12, 13]. To increase link connectivity and performance, we may use millimeter-wave/FSO hybrid

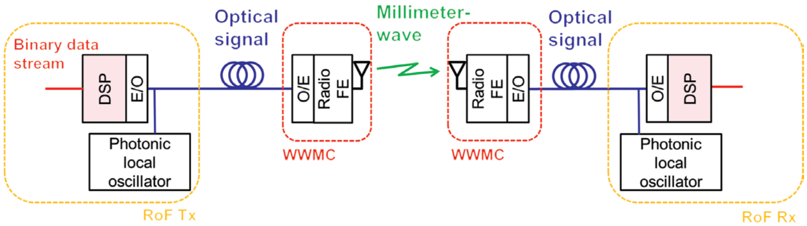

Figure 7 Seamless optical and radiowave connection.

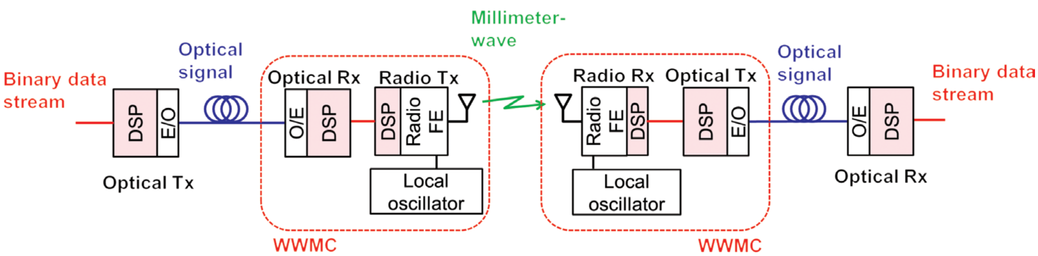

Figure 8 Combination of optical and radiowave links using conventional techniques.

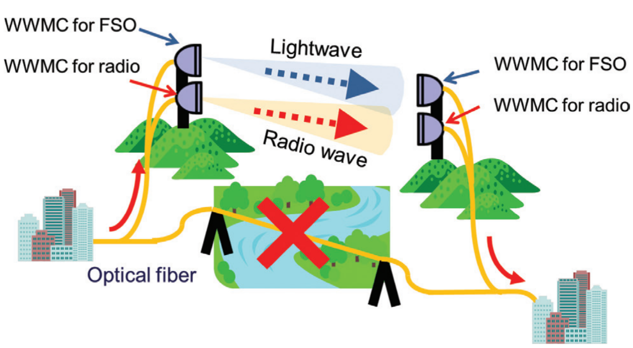

Figure 9 Wired and wireless seamless connection with radio and FSO links.

links shown in Figure 9 [11]. Such transmission technologies can also provide flexible operation of telecommunication services at ordinary times. For example, massive data transfer demands at temporary sites can be mitigated by RoF-based wired and wireless seamless transmission. These RoF systems would be useful for high-speed transmission in metropolitan and/or rural areas for particular purposes as well as for disaster recovery.

In a wired connection protection scenario as shown in Figure 6, during normal operation, called the 'baseband operational mode,' the RoF Tx transmits a high-speed optical baseband signal to the RoF Rx over an optical fiber. It is anticipated that the total capacities of around 1 Tb/s or more will be needed in future metro area networks owing to the spread of 40/100 Gigabit Ethernet (GbE) implementation. In this situation, the RoF Tx would play a role as a conventional optical baseband Tx, where the photonic LO is disabled. If the optical link between the Tx and the Rx is broken through an optical fiber cut, the operational mode of the RoF Tx will change to the 'RoF operation mode', which is suitable for radio transmission. In the RoF operation mode, the RoF Tx generates an RoF signal consisting of a baseband signal for data modulation and an photonic LO signal for direct photonic upconversion. This generated RoF signal is then transmitted to the WWMC, which consists of a simple O/R converter such as a photodetecter. The WWMC converts the received radio signal to an optical signal without changing the signal format, and the optical signal is then transmitted. Thus, this WWMC represents an alternative link that can act as the protection link for a cut optical fiber. The use of high-speed radio together with optical fiber transmission will generate protection links for enhancing network resilience. However, the transmission capacity would be smaller than that of 'baseband operation mode' because the available frequency bands for the radiowave connection are limited. The use of millimeter-wave signals is required for reduction of this capacity mismatch.

For 'last mile' situation including quick deployment of broadband connection such as a temporal link to temporal stations at a disaster recovery and within an optical fiber dead zone, a radio Rx should be set at these stations with the 'RoF operation mode' Tx. This radio Rx is comprised of a receiver antenna, a receiver FE including an analog-to-digital converter and a DSP, as shown in Figure 10. In the optical dead zone, an optical fiber may be deployed in future due to the demand of higher capacity connection. To prepare for this, the feature of both the

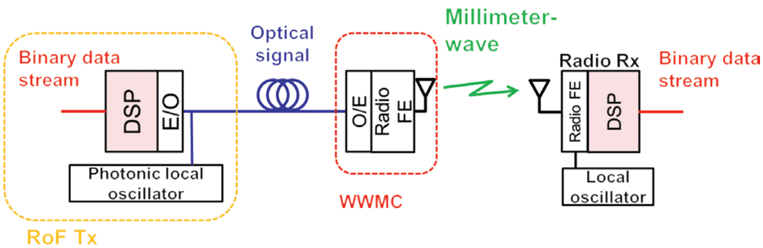

Figure 10 Seamless optical and radiowave connection for mobile terminals.

'baseband operation mode' and the 'RoF operation mode' should be implemented for the RoF Tx in advance.

6 Low latency transmission using wired and wireless links

In high-frequency trading for financial business, latency of a few milliseconds or shorter would have significant impact. In virtual environments, human beings can detect latencies as low as 10–20 ms, as reported previously [14]. Requirements on latencies depend on the applications, but they would be 10–200 ms for interactive services. Electromagnetic waves in the air propagate faster than in optical fibers, so that latency in wireless system would be smaller than in optical fiber communication (OFC) systems. For long-haul transmission, low earth orbit (LEO) satellites can provide low latency transmission, though physical path lengths of LEO links are larger than in OFC links. In LEO satellite transmission systems, payload signals are relayed through radiowave or FSO links, which would be shorter than a few thousand kilometers [15]. Figure 11 shows differences in latencies in LEO and OFC links, where $t_{L(LEO)}$ and $t_{L(OFC)}$ are propagation delays in LEO and OFC transmission systems [4]. When the altitude of the LEO satellites (h) is lower than 1000 km, the delay in LEO link systems are smaller than in OFC systems for links longer than 6000 km. Thus, for long-haul transmission, LEO satellites can reduce the latency. However, expected transmission capacity of LEO satellites would be much smaller than in OFC. We may consider networks consisting of wireless and wired links to mitigate demands for low-latency and high-capacity, simultaneously. For example, we can send some control signals to the receiver side via LEO satellites, while data for normal transactions are sent by optical fiber cables. When we detect rapid change of market, we can cancel the data for transaction already sent by OFC because the control signal in the air can overpass the data in optical fiber cables.

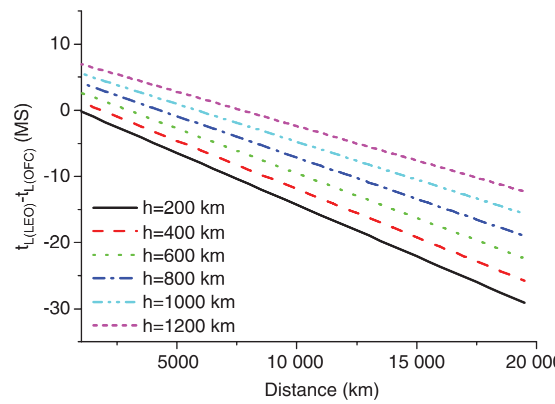

Figure 11 Differences in delays of LEO and OFC-based transmission.[4].

In addition to propagation delay of radiowave or lightwave, WWMCs should cause latency due to digital signal processing if we use conventional optical digital transmission and radiowave links as shown in Figure 10, where the WWMC should synthesize radiowaves from binary data streams. On the other hand, the WWMC based on RoF shown in Figure 9 can transfer waveforms without using DSPs, so that the latency in the conversion is very small. That implies wired and wireless seamless links can provide low-latency transmission because latency in WWMCs and wireless links would be smaller than in conventional transmission systems.

7 Discussion

As we have shown, transparent wave form transfer can make seamless integration of wireless and wired links for low-power consumption accessible networks. RoF-based WWMCs can convert lightwaves into radiowaves or radiowaves into lightwaves without using DSPs. Signal deformation in wireless and wired links is comprehensively compensated by DSPs at the RoF reciever in analogy with the end-to-end principle. Many simple WWMCs for transparent waveform transfer with powerful DSPs at the RoF transmitters or receivers would ease the difference between lightwaves and radiowaves as trasmission media.

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