Millimeter-Wave Radio-Over-Fiber Network for Linear Cell Systems

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(Invited Paper)

***Abstract*—We discuss and propose millimeter-wave linear cell systems for signal distribution on railway radiocommunication systems between train and trackside, and a foreign object debris detection system for airport runways using the radio-over-fiber network technology. Linear cell configurations based on wavelength-division multiplexing (WDM) and power-splitter-based distribution networks are discussed and demonstrated experimentally. A single-sideband modulation for data transmission in an intermediate frequency over a fiber system is successfully transmitted with an ultrafast wavelength-tunable laser diode for WDM routing to track the train car within 3 μs. Radar signal distribution by an optical double-sideband suppressed-carrier modulation mitigates the dispersion effect of the fiber cable to transmit a 32-GHz signal into the remote radar heads.**

***Index Terms*—Linear cell, millimeter-wave, radar, radio over fiber, train communication network.**

I. Introduction

COVERAGE of the service area in mobile radiocommunication systems is being spread to enhance connectivity of user terminals to the Internet by the development of third- and fourth-generation (4G) mobile communication systems. Now, even in mountainous areas, ubiquitous connectivity using handheld devices such as smartphones is established by terrestrial radio access networks; of course, satellite-based communication systems are still demanded in extreme environments. Microwave radio signals with wavelengths of 1 m or longer can be easily transmitted over the air to distant sites, owing to their long wavelength (smooth diffraction) and low atmospheric attenuation features. However, in next-generation mobile communication, 5G mobile, the frequency bands are changed from microwave bands to millimeter-wave bands in order to broaden the bandwidth: the expected throughput is up to 20 Gbit/s [1]. From the viewpoint of the coverage in the millimeter-wave bands, shorter wavelengths of radio signals increase the transmission loss, which is described by an inversely proportional feature to the square of the wavelength, based on the Friis propagation equation. In addition, atmospheric attenuation is drastically increased in the millimeter-wave bands, e.g., 8 dB/km at 60 GHz under standard atmospheric attenuation, although 20-GHz radio has the coefficient less than 0.1 dB/km [2]. In the scenario of mobile communication, a huge number of base stations/radio heads should be installed in the field, and therefore, the density of millimeter-wave radio units in the area is 100 times or greater than that in the microwave bands owing to 10-dB higher transmission loss. As all remote radio stations/radio heads should be connected to backbone networks, it will be difficult to establish physical links in both optical (wired) and radio (wireless) manners between a central office and many remote heads. In addition, these mobile communication signals will have a bandwidth greater than 500 MHz and up to several GHz; therefore, conventional link techniques could not be sufficient to transport the signals.

Waveform transport technology—simple analog-modulation-based signal transmission—is based on a traditional technique for direct transmission of signals. Advanced development of photonics and electronics devices helps to realize precise signal generation and accurate control. Therefore, the signal can be transmitted over optical/electrical waveguides, and even over the air using high-frequency radios, with keeping its waveform [3], [4]. Radio over fiber (RoF) is a part of a waveform transport technique of radio signals via an optical fiber. Current high-speed optical modulator and photodetector can realize transport of broadband radio signals over the fiber [5]–[7]. Nevertheless, RoF links might have a problem with the establishment of connections between a central office to many remote radio heads because a huge number of optical fiber cables should be installed everywhere. However, this is still applicable to some specific situations, such as linear cell systems.

A linear cell system has a cell configuration of coverage cells located linearly along the service area, for example, railways, highways, and airport runways (Fig. 1) [8]–[12]. In the system, radio heads would be set along the service area linearly, and optical fiber cables will therefore be easily installed along with

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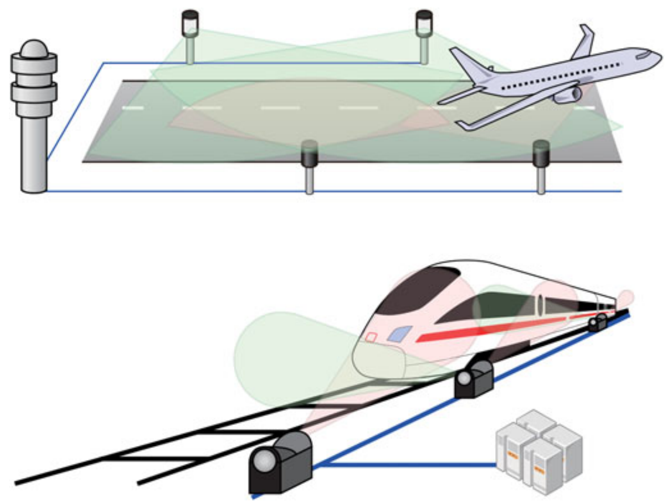

Fig. 1. Schematic illustration of the applications of linear cell systems for (top) airport runway and (bottom) railway track.

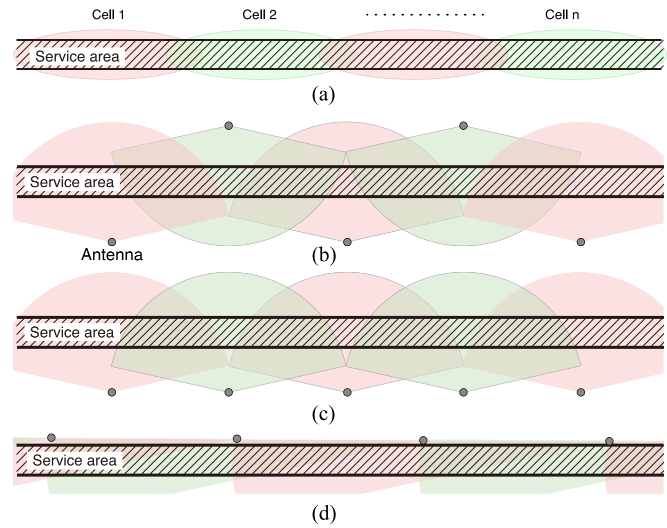

Fig. 2. Schematics of (a) linear cell system concept, and its implementation case of (b) staggered, (c) one-sided, and (d) monodirectional antenna configurations.

the cells; it is generally not necessary to cover a two-dimensional area. Moreover, a simple configuration of coverage cells allows the use of modified gain antennas in the radio system; thus, the transmission distance of the radio signal could be extended, even in millimeter-wave bands. Especially in train systems, the operation direction center (ODC) of the system has train location information (TLI), which includes the location and velocity of each train car. A central office for communication can activate the remote heads where the train is heading, and transfer the signals to the appropriate remote heads over the network. These linear cell systems will become a possible application of millimeter-wave distributed antenna systems in an early stage of installation of the millimeter-wave field systems.

In this paper, we discuss the configuration of linear cell systems, especially on a railway radiocommunication system between train and trackside (RSTT) and an airport-runway-surface surveillance system. The architecture and configuration of the RoF signal transport system are discussed in Section II, along with a proof-of-concept demonstration of a wavelength-division multiplexed (WDM) RoF signal transmission with a high-speed wavelength-tunable laser diode (TLD) to switch the wavelength channels to remote radio heads. A foreign object debris (FOD) detection system for airport runways based on a 96-GHz radar system driven by RoF network technology is also discussed.

II. Linear Cell Systems Connected to RoF Network

The design of cell coverages in radio communication systems is key for the realization of high throughput and high connectivity features in the radio services. In mobile communication systems, such as traditional 4G and even in future 5G mobile, in principle, service areas are designed to cover broad areas such as buildings, agriculture fields, and towns. In this situation, an antenna at each remote radio head should have omni-directivity or sector-based directivity to cover a 360° area. Conventional microwave radio systems are readily applicable for this configuration because of their low transmission losses; however, in future millimeter-wave bands, high transmission losses, which include atmospheric attenuation and a propagation loss, require a high effective isotropic radiation power (EIRP) to maintain the expected transmission distance. In this case, although the application of high-gain antennas is a promising solution to obtain high EIRP to provide radio signals to the devices, high EIRP requires both high output power of amplifiers and a high directivity antenna. Generally, the high directivity of the antenna limits the coverage area. In this scenario, a beam-steering technique will be equipped to switch the beam direction to each user terminal based on phased-array antenna technology with a phase-control network and amplifiers. These steering techniques are now being developed in the millimeter-wave bands, and still have issues for the realization of wide-angle steering. Thus, millimeter-wave radio with broad coverage is currently difficult to realize via current electronics and photonics technologies.

In a linearly located distributed antenna system, i.e., a linear cell system, a coverage cell is designed along with the service area, such as a railway track, a highway road, or an airport runway [8], [10]. Fig. 2(a) shows a conceptual diagram of a linear cell system. Coverage cells are located in a linear arrangement with small overlaps to cover the area. In this configuration, there is no limitation of radio spectrum uses and location of remote radio heads. In real applications, such as railways and airport runways, remote radio heads cannot be settled at the center of the coverage cells. Therefore, these radio heads should be located at the sides along the coverage area [Fig. 2(b)–(d)]. We have two ways to simply design the antenna locations: along both sides or a single side. Particularly in staggered configurations [Fig. 2(b) and (c)], cell overlaps can be efficiently designed for the enhancement of resolution in radar systems; however, each remote radio head should have a wide-angle coverage in this design. The other solution is comprised of a monodirectional antenna and an elliptic- or sector-form cell structure covered by remote radio heads set along a single side of the coverage area [Fig. 2(d)]. In this case, higher-gain antennas can be used to cover the linear cells, and can extend the possible transmis-

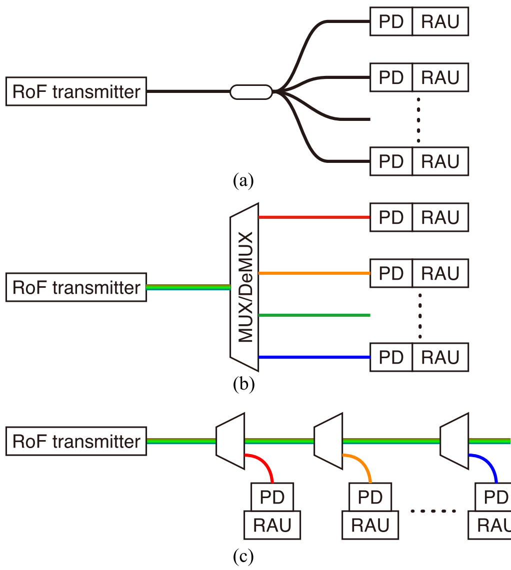

Fig. 3. Schematics of optical network systems for (a) power splitter-based passive double star, (b) WDM passive double star, and (c) WDM bus configurations.

sion distance by their high EIRPs. The high EIRP will also increase the signal-to-noise power ratio (SNR) of the radio signal at the receiver, thus enhancing the signal quality as well as the throughput. This linear cell system is capable of both radio communication and distributed radar system operation; the network configurations have small differences for signal transport from a central office to radio heads.

We have two simple architectures for transmission of the signal through the network connected to the linear cell system: simple power-splitting and WDM-based passive double-star networks (Fig. 3). The former case, shown in Fig. 3(a), is suitable for transmission of the same signal, such as a clock signal, to the remote stations; for example, transmission of the seed radar signal via the network to remote radar heads helps to realize a distributed radar system and a synthesized aperture radar system. However, when applied to the communication systems, a time-division-multiplexing scheme should be implemented in this configuration. The same applies to a passive optical network, such as fiber to the home. A WDM network is also applicable for communication systems because wavelength channels are independent of other channels for the realization of simultaneous transmission features. Because many transmitter units are installed in a central office and remote stations for WDM systems, installation costs, including energy consumption for stabilizing the wavelength of the laser in the transmitter, will be higher than those for splitter-based distribution networks in general. A WDM bus configuration is another candidate for a WDM-based linear cell network [Fig. 3(c)]. In this system, a WDM multiplexer (MUX) and demultiplexer (DeMUX) should be installed at each point connected to a radio access unit (RAU).

In the WDM case, the capacity of a number of wavelength channels is a key factor for the reduction of installation costs of the optical fiber cables. In particular, railway tracks in tunnel areas do not have enough space for the installation of additional fiber cables. In addition, transmission loss in the millimeter-wave band, such as E-band (60–90 GHz) and W-band (75–110 GHz), limits its transmission distance up to several km, even in clear weather conditions. Therefore, the distances between the antennas would be shorter than several km. As high-speed trains, such as a Maglev with a speed of up to 500 km/h, pass 1 km in less than 10 s, the hand-over processes between the RAUs and terminal will often occur in a conventional way for the connection, and thus, the throughput of the connections will be drastically degraded in high-speed railway systems. To improve the throughput, moving-cell architecture is a promising solution to realize hand-over-free connections [13], [14]. A node base station (NBS), which works as a centralized RoF transmitter, manages an RoF signal transmission path to suitable RAU near the train. When the train passes the RAU, the NBS switches the path to the next RAU. In this scenario, the RAU seems to be tracked along with the train cars; finally, the hand-over process cannot occur. To maintain the connection in 10 min. (600 s), 60 wavelength channels, which are assigned to 60 RAUs managed by one NBS, should be received in the fiber cable. Considering up-stream and down-stream multiplexing in a single fiber core, we should receive 120 wavelength channels in a single core; the separation of the WDM channels in the C band is configured to at least 50 GHz. The details of the network configuration for RSTT and FOD detection (FODD) system are discussed in the next section.

Application of a multicore fiber (MCF) is a possible solution as an alternative to WDM configuration. The MCF can directly reduce the required number of wavelength channels, thereby decreasing the total transmission loss in the optical fiber [15]. The MCF might be useful for a beam steering technique in the RoF system. Non-mechanically moved antenna units for both radar and communication systems in millimeter-wave bands are demanded for the reduction of maintenance costs. A phased-array antenna, which is comprised of many independent antennas, directly connected to the MCF can form arbitrary beam shapes by tuning the phases of the transmitted signals in the MCF [16]. The MCF has a great advantage on the stability of actual optical path lengths in each core, rather than a bundled fiber. However, at this time, multicore MUX/DeMUX still has problems in cost and tolerance; therefore, the RoF network using MCF will be realized in future.

III. WDM RoF Network for Railway Radiocommunication Systems Between Train and Trackside

RSTT-optimized linear cell systems are based on a WDM network because an NBS, as a central office, should operate many track-side RAUs (TS-RAUs) independently and simultaneously [17], [18]. In this sense, a logical single-star configuration is suitable; however, a physical single-star configuration is not applicable to the RSTT due to the limitation of space for installation of the fiber cables. Therefore, a WDM-based network configuration with a WDM router on a passive double-star architecture is considered in this section. In principle, generation of the millimeter-wave signals at the TS-RAU is still

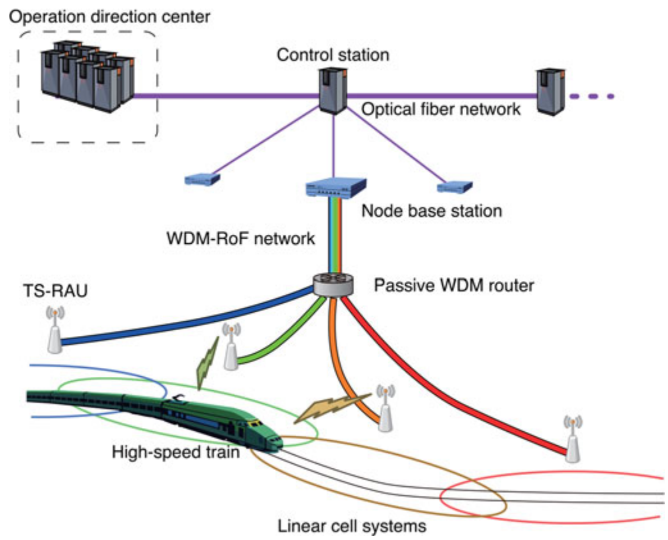

Fig. 4. Conceptual diagram of RSTT by WDM-RoF network.

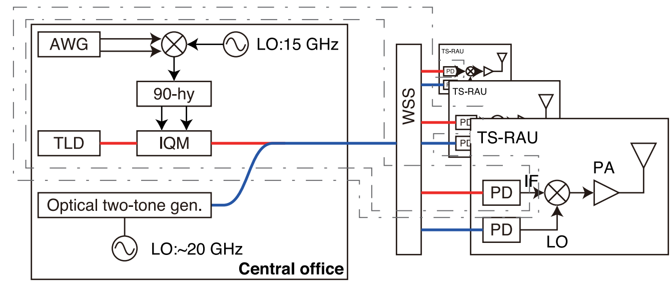

Fig. 5. Configuration of WDM IFoF system for RSTT. The dashed box and dashed-dotted box indicate the actual experimental setup for IFoF evaluation and the setup for WDM switching in the paper, respectively.

rather difficult, owing to the higher cost and energy consumption of millimeter-wave integrated circuits in higher millimeter-wave bands, such as the W-band. To reduce the complexity of the configuration of the TS-RAU, waveform transportation using an analog RoF technique is considered to be deployed in the RSTT WDM network. In this case, the dispersion effect of an optical fiber can degrade converted electrical signal throughput by transmission of the fiber [19]. For instance, double-sideband (DSB) modulation at an operating frequency of 10 GHz could not deliver the 10-GHz radio signal to a receiver when the optical fiber transmission distance was approximately 30 km with a dispersion coefficient of 17 ps/nm/km. In railway tracks, as the expected length of the optical fiber cable is up to 30–40 km (as mentioned in the previous section), an RoF signal could be sharply degraded during throughput by the dispersion effects. Moreover, a large difference of distance between the NBS and each TS-RAU cannot manage the fiber lengths precisely without installation of dispersion compensation fibers. Single-sideband (SSB) modulation is a promising scheme against the dispersion effect [20]. In addition, the wavelength spectral efficiency of the SSB is approximately doubled to that of the DSB; thus, it is a significant advantage in the capacity of wavelength channels in a single-core fiber. In this study, a 15-GHz intermediate frequency (IF) component is considered for the WDM RoF signal because of the spectral efficiency and bandwidth of an optical modulator.

Fig. 4 shows a schematic of the RSTT system with the WDM-RoF system. An ODC transmits information, including a TLI and the data requested from train cars (such as a download data from the Internet), to an optical carrier station (OCS), one of which is located every 100–150 km. A control station (CS) connected to each OCS works as a gateway of the train access network to the backhaul network. The NBS performs as a radio base station, which is operated by a CS, to transmit the radio signals through a WDM-based RoF network to each TS-RAU via a WDM router. Finally, a TS-RAU converts the received RoF signal into a millimeter-wave radio signal, irradiated to the train cars. The CS operates the NBSs by obtaining the TLI for the suitable signals to be transported into the nearest NBS to the train cars. Each NBS, located every 30–50 km along the railway track, operates 30–50 TS-RAUs to track the train car by optimization of the signal transmission route in the WDM network. The train cars can receive the radio signal from the moving virtual NBS owing to the prediction and tracking of the train car position with the TLI. The hand-over-free connection will be established in the WDM RoF network connected to one NBS. This scheme is similar to the moving-cell configuration designed for 4G and 5G mobile. It is important that a linear cell system and the precise TLIs collected by the ODC in the RSTT can realize a part of the coordinated multi-point technology more easily than the standard mobile communication systems, because all the TLIs are gathered to the ODC.

We evaluate and demonstrate the proof-of-concept demonstration of the WDM-RoF network using an optical SSB modulation at a frequency of 15 GHz. Fig. 5 shows an example of an RSTT downlink [a central office (CO) used as an NBS to TS-RAUs] configuration. A data signal is generated by an arbitrary waveform generator (AWG) with two channels (in-phase and quadrature phase signals), and is input to an integrated IQ mixer (Keysight technologies E8267D) operated at a local oscillator (LO) of 15 GHz to upconvert a 15-GHz IF signal. Generated patterns by the AWG are non-return-to-zero on-off keying signals with a pseudorandom bit stream, whose length is $2^{15}-1$, for generation of a quadrature phase-shift keying (QPSK) signal. The modulation speed is 1 Gbit/s. A 90-degree hybrid (90-hy) divides in-phase and quadrature phase signals at 15 GHz input into an optical IQ modulator to generate an SSB signal. The optical IQ modulator is operated by an ultra-fast TLD, whose switching speed is achieved up to 3 μm in the C-band following the 50-GHz dense WDM grid [21]. On the other hand, an optical two-tone generator (based on a DSB suppressed-carrier modulation for frequency doubling, or higher-order modulation utilized for optical frequency quadrupling) provides an optical signal with a frequency separation of 80 GHz. For example, a high-extinction-ratio optical intensity modulator operating at 20 GHz with relatively large RF input power can generate a $\pm$2nd-order harmonic component at a modulation bias point set to a maximum transmission point in the transfer function, and then an optical notch filter suppresses a carrier component to form a two-tone signal with a frequency separation of

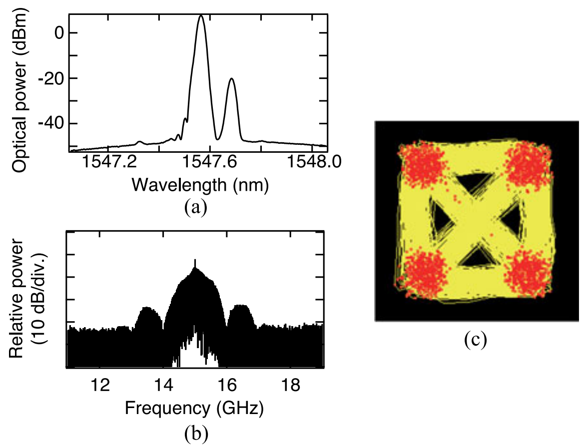

Fig. 6. (a) Obtained optical spectrum of SSB signal at a frequency of 15 GHz, (b) power spectrum of converted 15-GHz IF signal at the receiver, and (c) demodulated constellation maps of QPSK.

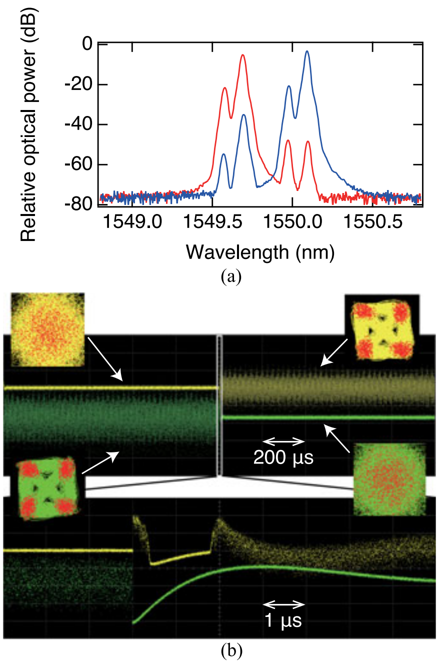

Fig. 7. (a) Optical spectra of wavelength channels 1 and 2, and (b) temporal evolution of the PD output signals with demodulated constellation maps at each point. Enlarged temporal evolution is also shown as guideline.

80 GHz. The SSB and two-tone signals are combined by an optical coupler to transmit over an optical fiber cable. A wavelength-selectable switch based on a liquid-crystal-on-silicon device is used as a passive WDM splitter to distribute the WDM signal with the optical two-tone signal to remote TS-RAUs. In the TS-RAU, a photodiode (PD) converts the IF-over-fiber (IFoF) signal and two-tone signal into the IF and 80-GHz LO signals, which mix to upconvert a 95-GHz signal by the RF mixer. A power amplifier and antenna optimize an RF power and then irradiate the signal into the air. This configuration is only described on the downlink; however, the uplink (TS-RAU to CO) could be configured with a similar architecture. For the SSB signal generation and demodulation, we evaluate the signal quality under a point-to-point configuration without the WSS and two-tone generator in only the optical domain.

Fig. 6 shows an optical spectrum of the SSB signal at 15 GHz and demodulated constellation maps at an IF receiver. The unwanted spurious (upper sideband, USB) component is suppressed with 30 dB or more, and the expected occupied bandwidth is less than 25 GHz; a 50-GHz grid can be applicable for the SSB IFoF network. It should be noted that the AWG generated 1-Gbit/s pseudorandom bit streams with a rectangular pulse shape: 2 Gbit/s QPSK. The demodulated QPSK signal has clear symbol separation with an expected error vector magnitude (EVM) of less than 14% under a radio back-to-back configuration (observed at the output of the photodiode). The signal quality will be improved by application of equalization in the digital signal processing domain at the receiver as well as at the transmitter by a pre-distortion technique.

For the realization of train-car-tracking features using the passive double-star configuration, an active WDM routing system should be employed. Simply, we have two methods for the routing technique: active WDM switching at the router and an implementation of a wavelength-tunable laser in the transmitter in the central office. The former limits the throughput of the network, owing to its low switching speed of up to several ms. An increase of the guard time between the packets will reduce the throughput. On the other hand, the TLD system has potential advantages in terms of cost and speed. In this study, we use the ultra-fast TLD for switching the wavelength channels. Fig. 5 (dashed-dotted box) shows a proof-of-concept demonstration setup with three WDM channels. An SSB QPSK signal at 15 GHz (IFoF) is used as a signal under test for transport and switching. The WSS is set for 50-GHz arrayed-waveguide grating device configuration. Each output channel has a separation of 50 GHz. First, we evaluated two-WDM-channel switching with demodulation (Fig. 7). The obtained spectra show a USB suppression ratio of the SSB signal of 30 dB, the same as the experiment described above. However, a residual signal, owing to leaks from the adjacent WDM channels, has a suppression of approximately 30 dB. This obtained ratio is comparable to the extinction ratio of the WSS, and therefore, the improvement of the WSS will enhance the suppression ratio, although the residual signals are already sufficiently small. For evaluation of switching behavior, two WDM signals are switched to the other channel per second. In the temporal evolution, dead time by tuning the wavelengths is less than 4 μs, which is limited by the speed of the control board and its sequences of the TLD. In this sense, it is possible to set a guard time of the packets less than 10 μs; throughput of the packet could not be degraded by fast switching. The signal quality of each channel is less than 15% in EVMs.

Three WDM channels are also evaluated in Fig. 8. The obtained switching time is comparable to the configuration with two WDM channels, described above. Thus, this architecture has scalability on the wavelength channels without degradation of the switching speed; therefore, the WDM switching technique using the TLD under IFoF configuration is capable for the WDM RoF network to track the high-speed train car.

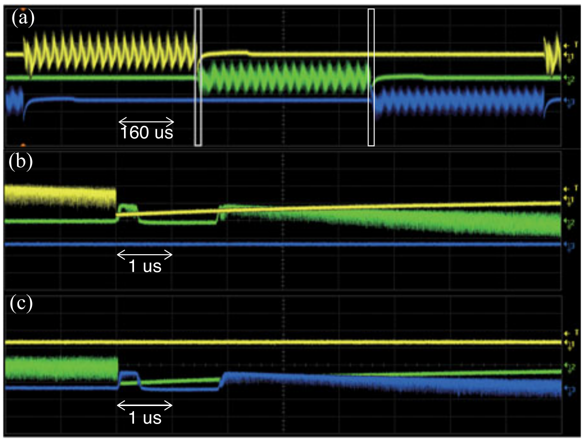

Fig. 8. (a) Temporal evolution of three WDM channels switching with (b) and (c) their enlarged behavior in time domain at switching points.

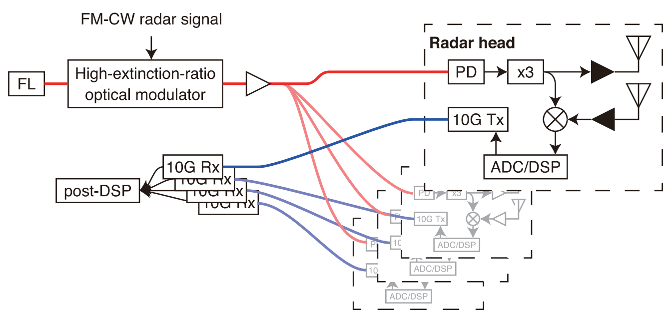

Fig. 9. Linear cell radar system configuration with four remote heads.

IV. RoF-Network-Connected Linear Cell Radar System for FOD Detection in Airport Runway Surfaces

The millimeter-wave radar system has a principle limitation of a detectable range owing to its high transmission loss; however, only millimeter-waves can detect small FODs by their short wavelength feature. To satisfy both the large coverage and small FOD detections, a distributed radar system in the millimeter-wave band should be configured [22]–[24]. An RoF network can help to realize the distributed radar system under linear cell configurations described above to cover a long service area; for example, a typical airport runway of 3000 m × 60 m. In radio regulations, a frequency band of 92–100 GHz, with a bandwidth of 8 GHz, has already been allocated to radiolocation services; the wavelength of approximately 3 mm can be useful for detection of 2.5-cm diameter/height pillars [25]. In addition, a range resolution of frequency-modulated continuous-wave (FM-CW) is described by $\Delta R = c/2f_{BW}$, where ΔR, c and f_{BW} denote the range resolution of the FM-CW radar, the speed of light, and a sweep bandwidth of the FM-CW signal, respectively. In this case, the 8-GHz bandwidth theoretically provides a resolution of approximately 1.8 cm; thus, 2.5-cm (1-inch) FODs with a separation of 2.5 cm can be detected using 92–100 GHz FM-CW radar systems [26], [27].

Fig. 9 shows a block diagram for a distributed FM-CW radar system. A radar signal synthesizer is located in a CO to generate a seed triangle-shaped FM-CW signal at a center frequency of 16 GHz with a bandwidth of 1.33 GHz. As a high-extinction-ratio optical modulator connected to a fiber laser (FL) is operated under a double-sideband suppressed-carrier (DSB-SC) operation under a modified operation condition in bias voltages, optical two-tone signals with a frequency separation of 32 GHz, which are doubled from the input signal, are provided at an optical modulator output. An erbium-doped fiber amplifier (EDFA) boosts the optical signal, and the signal is then split into four signals by an optical power splitter to distribute four remote radar heads. After an optical fiber transmission, a photodiode (PD) equipped with the radar head converts the 32-GHz-separated RoF signals into 32-GHz radio signals. After the signal passes through a frequency tripler (×3), a power coupler, and a power amplifier (PA), a high-gain antenna, with a gain of approximately 40 dBi, irradiates the 92–100 GHz FM-CW signal into the air. The reflected signal from a target is collected by an antenna with the same gain as the transmitter and is amplified by a low-noise amplifier (LNA). An LO signal split by the coupler in a transmitter section, and the received RF signal is mixed and frequency-downconverted to an IF signal by a mixer; then, an IF amplifier optimizes a power level of the IF signal. An analog-to-digital converter (ADC) with a resolution of 14 bits digitizes the IF signal into a digital signal processor, which performs a fast Fourier transform for identification of the frequency of the IF component. The digitized signal is transmitted using a 10-Gbit Ethernet transmitter (Tx) and receiver (Rx) to the CO, and then the CO provides the centralized post-processing for ranging and composition of the images.

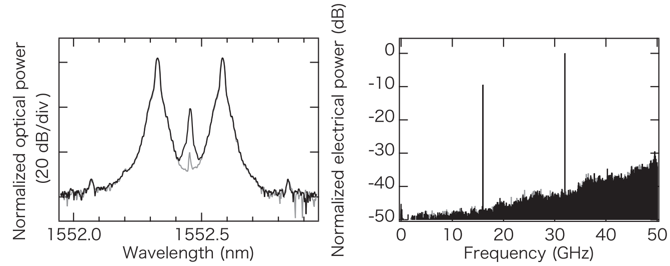

Fig. 10. (Left) Optical two-tone spectra under (black) 40-dB extinction ratio operation and (gray) 60-dB high-extinction ratio operation, and (right) the converted electrical power spectrum.

The optical spectra generated by the 16-GHz CW input is shown in Fig. 10. In this configuration, the operating bias point of the high-extinction-ratio modulator is not set at a null point of the transfer function because the null-point operation has an instability on the small-bias drift of the modulator. We set the slope of the transfer function with a relative extinction ratio of 40 dB; this extinction ratio is sufficient to provide a spurious suppression ratio greater than 15 dB in an electrical domain. Moreover, the spurious component has a half of the frequency that can be quickly suppressed by insertion of a bandpass filter.

Expected coverage of each radar head is a key for the design of the cell size and location of radar heads. Fig. 11 shows ranging results with various target distances from the radar head. A metal pillar with a diameter and height of 2.5 cm is used as a standard FOD for detection, which has a corresponding radar cross section in 90 GHz of approximately −20 dBsm. The obtained IF power from the FOD has a clear inversely proportional

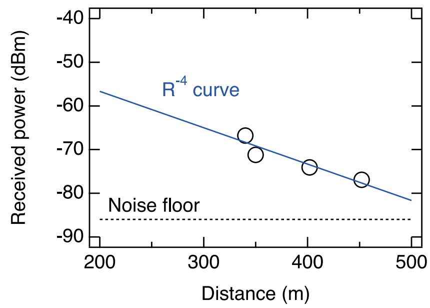

Fig. 11. Received IF power for a 2.5-cm metal pillar set at several distances from the radar head. The blue and dotted black lines denote a fitting curve of the inverse of quadruple the distances and the system noise level, respectively.

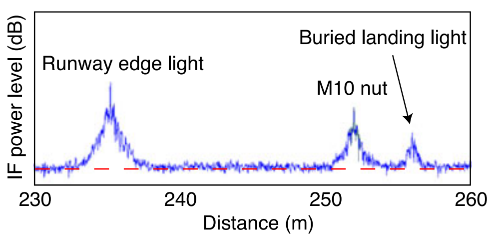

Fig. 12. An example of detection results of runway edge light, M10-size nut, and buried light in the landing area by the radar system. The red dashed line indicates the system noise level.

relationship to a quadruple of the distance. This is because the received power of the radar system is described by $P_t G^2 \lambda^2 \sigma/(4\pi)^3 R^4$, where P_t, G, λ, σ, and R denote the transmitter power of the radar, antenna gain, wavelength of the radar signal, radar cross section, and distance, respectively. The figure shows a successful operation of the radar system. When the FOD is set at 450 m, a received IF signal has approximately -77 dBm, which is 9 dB greater than the system noise level. Therefore, one radar head has coverage of at least 450 m for detection. The results will provide a guideline for the design of the cell.

This linear cell radar system is now evaluated in a field trial at Narita International Airport, Narita, Japan, as a proof-of-concept demonstration [28], [29]. An antenna in each radar is rotated 360 degrees every 4 s. In this way, moving objects on the runway can be detected in less than 10 s by difference detection with the comparison of the last and current results. An example of ranging results is shown in Fig. 12 under the field trial. The radar head is located approximately 220 m away from the center line of the runway. The clear echo signal is detected from a runway edge light, which is located 30 m from the center line. Buried light equipment on the center line in landing area is also detected with an SNR of approximately 8 dB. An M10-size nut, which is set on the runway for FOD under test, can be detected by the system; therefore, the linear cell radar system can detect the small FOD on the runway.

V. Conclusion

Linear cell systems empowered by an RoF network are discussed for application to RSTT and FODD systems. In both cases, an optical fiber dispersion would be a critical issue. An optical two-tone technology using an optical SSB modulation and the DSB-SC signal generation can mitigate this effect to distribute the signal over the fiber network. WDM switching using fast-TLD can dramatically improve the throughput by tracking the train cars. The RoF-based linear cell system is capable for a network requiring low latency in particular fields, such as highway autonomous vehicle operation and Maglev RSTT. Moreover, a sensor-over-fiber system, such as the linear cell radar system, will enhance civil security and safety for obstacle and intruder detection for critical facilities with moderate costs.

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