Multiplexed Transmission of Uncompressed HDTV Signals Using 120-GHz-band Millimeter-wave Wireless Communications System

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Abstract

We have succeeded in the world's first trial of transmitting six-channel uncompressed high-definition television (HDTV) streams over a wireless system in joint experiments with Fuji Television. The wireless communications system is composed of (1) a 120-GHz-band millimeter-wave wireless link that can transmit either 10GbE (10 Gigabit Ethernet) or OC-192 signals and (2) an i-Visto system that can deliver and store uncompressed HDTV streams over IP (Internet protocol) networks in real time. The wireless link meets the increasing demands in TV stations for an ultrabroadband wireless communication system that can transmit multiplexed HDTV signals in large-scale live relay broadcasting of HDTV programs.

1. Introduction

A wireless link system that can transmit uncompressed high-definition television (HDTV) signals has been strongly desired, because TV program production based on the HDTV standard is spreading rapidly in TV stations due to the start of digital TV broadcasting. In Japan, digital broadcasting started with broadcast satellite (BS) transmissions in December 2000, and the number of households receiving BS digital services exceeded ten million in August 2005. Terrestrial digital television broadcasting began in Japan in December 2003 in the Tokyo, Osaka, and Nagoya metropolitan areas and is scheduled to spread to all principal cities of Japan by the end of 2006. An uncompressed HDTV signal (HD-SDI: high definition serial digital interface) requires a data rate of 1.5 Gbit/s. For wireless transmission of broadcast materials, a 7- or 10-GHz-band microwave field pick-up unit (FPU) is commonly used. The data rate of the state-of-the-art FPU is 3–80 Mbit/s, so no existing microwave wireless communications systems can transmit uncompressed HD-SDI signals. Therefore, current microwave wireless communications systems must compress the HD-SDI signal with MPEG or JPEG2000 encoders. This compression causes a time delay, which makes it difficult to edit programs or switch cameras in a live broadcast. Uncompressed HD-SDI signals can be transmitted over optical fibers, but that limits the relay broadcasting locations.

Millimeter-wave (MMW) technologies are suitable for increasing the data rate of wireless communications systems because the data rate depends on the carrier frequency [1]. Wireless communications systems using 60-GHz-band MMWs have a data rate of over 1.5 Gbit/s and can thus transmit one channel of uncompressed HD-SDI signals. However, large-scale live relay broadcasts, such as golf tournaments and music concerts, need multiple channels of uncompressed HD-SDI signals. No existing wireless communications systems using a carrier frequency below the 60-GHz band have the capacity for multiplexed uncompressed HD-SDI transmission. For this purpose, a wireless link system that uses a carrier frequency of over 100 GHz is a promising approach.

We have been developing a 120-GHz-band wire-

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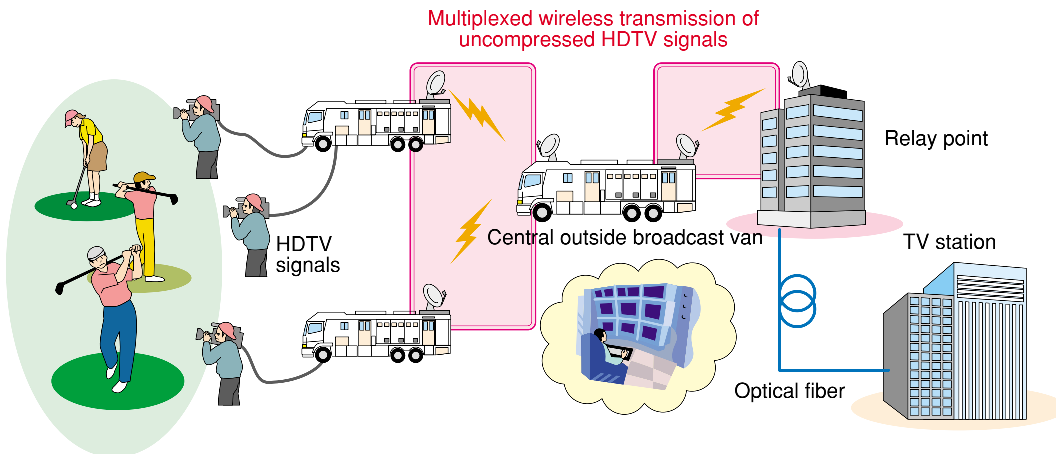

Fig. 1. Large-scale relay broadcast using ultrabroadband wireless communications.

less link system that has a data rate of 10 Gbit/s [2]. The wireless link system uses photonic technologies for the generation, modulation, and transmission of MMW signals, because photonic components have wider bandwidths than electronic components and we can construct an over-100-GHz system with currently available components. The 10-Gbit/s-wireless link system has sufficient capacity for multiplexed transmission of uncompressed HD-SDI signals.

The combination of the 120-GHz-band wireless communications and fiber networks will enable large-scale live relay broadcasting of HDTV programs. Relay broadcasting using ultrabroadband wireless communications is schematically shown in **Fig. 1**. The HD-SDI signals are gathered and multiplexed at the outside broadcast vans and transmitted to the central outside broadcast van by ultrabroadband wireless communications. The multiplexed signals are sent from the central outside broadcast van to the relay point building in which broadband fibers are installed and then transmitted to the TV stations through optical fibers. These ultrabroadband wireless links connected with the fiber networks will facilitate the production of HDTV programs. However, technology for multiplexing HD-SDI signals over broadband IP (Internet protocol) networks is required to achieve the relay broadcasting shown in Fig. 1.

In this paper, we report on our investigation of multiplexed transmission of HD-SDI signals over a 120-GHz-band wireless link. We used the i-Visto gateway (see section 2.3) to multiplex HD-SDI signals [3]. It generates a video stream of IP packets from HD-SDI signals captured by existing HDTV devices and delivers them through high-speed IP networks, such as OC-48* with a transmission rate of 2488.32 Mbit/s or 10GbE (10 Gigabit Ethernet) with a rate of 10 Gbit/s. We have demonstrated six-channel (6-ch) multiplexed wireless transmission of HD-SDI signals using the 120-GHz-band wireless link and i-Visto gateways.

2. 120-GHz-band wireless communications system

2.1 System configuration

2.1.1 Transmitter

The transmitter of the wireless link is composed of a 125-GHz photonic MMW generator [2], a data modulator, and the core with an antenna. A schematic and photograph of it are shown in **Figs. 2** and **3(a)**, respectively. The core of the transmitter is composed of a Cassegrain antenna with a diameter of 450 mm and equipment that integrates a photodiode module and DC circuit boards.

The photonic MMW generator is used to generate an optical signal whose intensity is modulated at 125 GHz. The output of an ultranarrow linewidth single-mode laser (SML) is modulated at a frequency of 62.5 GHz using the carrier suppression method. A $LiNbO_3$ Mach-Zehnder modulator (MZM) is used for modulation. The modulated optical signals are fed into a planar lightwave circuit (PLC) that integrates an arrayed waveguide grating (AWG) and a 3-dB combiner. The two output channels of the AWG with a spacing of 120 GHz are connected by a 3-dB com-

* OC-48: OC stands for optical carrier. OC-48 is one of the traffic capacity levels defined by SONET (synchronous optical network).

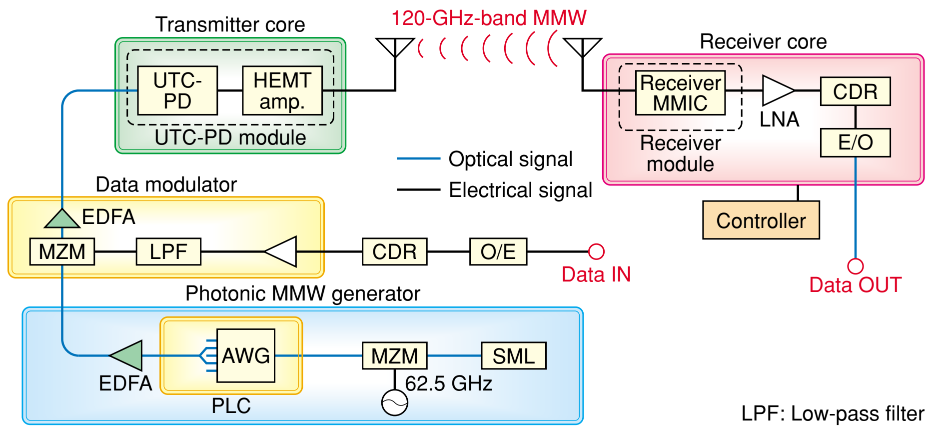

Fig. 2. Schematic of 120-GHz-band wireless link.

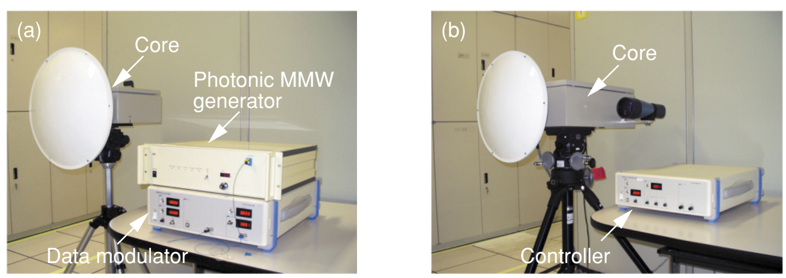

Fig. 3. Photographs of (a) transmitter and (b) receiver.

biner. The PLC acts as an optical filter that outputs two modes whose frequency interval is 125 GHz, and the resulting optical signal-to-noise ratio is over 40 dB. By connecting the AWG and the 3-dB combiner via optical waveguides in the PLC, we keep the phase difference between the two modes constant, which reduces the phase noise of the generated MMW signal. The phase noise of the MMW signals is below –75 dBc/Hz at an offset frequency of 100 Hz [2]. The output signal is amplified by an erbium-doped fiber amplifier (EDFA).

The data modulator modulates the output of the optical MMW generator with 10-Gbit/s data signals. For the modulation, we used a conventional MZM. Many communication network standards, such as OC-192 (9953.28 Mbit/s) and 10GbE, use optical fibers for 10-Gbit/s data transmission. Therefore, we use an optical-to-electrical (O/E) converter and a clock and data recovery (CDR) circuit in the data signal circuit. The optical signal modulated by data signals is amplified by another EDFA.

In the transmitter core, the optical signals are O/E converted, amplified, and radiated via a high-gain antenna. This is done by feeding the optical signal from the data modulator into the uni-traveling carrier photodiode (UTC-PD) module [4], which is composed of a UTC-PD and an MMW amplifier [5]. The primary features of a UTC-PD are fast response, high operating current, and high saturation power, which originate from its operating mode in which only electrons act as active carriers. The MMW amplifier uses 0.1-µm-gate InAlAs/InGaAs high-electron-mobility-transistors (HEMTs) [5]. The HEMT amplifier has a gain of over 20 dB at 125 GHz, and the UTC-PD module can generate output power of over 10 dBm at 125 GHz. The generated MMW signal is radiated from a high-gain Cassegrain antenna with a diameter of 450 mm.

2.1.2 Receiver

The receiver is composed of a receiver core and a controller. A schematic and photograph of it are shown in Fig. 2 and **Fig. 3(b)**, respectively. The receiver's core consists of the receiver module, baseband amplifier, CDR circuit, and E/O converter. The controller acts as a DC supply. A high-gain Cassegrain antenna with a diameter of 450 mm is attached to the receiver core. The received MMW signal is amplified and demodulated by a receiver module, which uses a receiver monolithic microwave integrated circuit (MMIC) chip [5]. The demodulated data signals are amplified by a low-noise amplifier (LNA). They are input to the CDR and converted to an optical signal by the E/O converter.

2.2 Transmission characteristics

We obtained an experimental radio station license from the Japanese Ministry of Internal Affairs and Communications on August 2005 because legal controls are imposed on the emission of radio waves outdoors. The specifications of the wireless link are shown in **Table 1**. The center frequency is 125 GHz, the occupied bandwidth is from 116.5 to 133.5 GHz, and the maximum output power is 10 dBm. The radio station is registered as a Cassegrain antenna with an antenna gain of 48.8 dBi.

We measured the bit-error-rate (BER) characteristics of the wireless link at a data rate of 9.953 Gbit/s, which corresponds to the data rate of the OC-192 standard, and succeeded in achieving error-free transmission of an OC-192 signal with a BER of less than 10^{-12}. The input and output data signals were both optical signals transmitted through fibers, as shown in Fig. 2. The transmission distance was 200 m. Between the transmitter and receiver, we placed a glass window with transmission loss of about 9 dB, which suggests that the link could transmit 10-Gbit/s data over a free-space distance of 600 m. We estimated the maximum transmission distance from the minimum received power for error-free transmission, maximum output power, and antenna gain. In fair conditions, the maximum transmission distance was about 1.5 km to achieve a BER of less than 10^{-12} and 2.5 km for 10^{-4}.

The received power is reduced drastically by rainfall attenuation, obstacles such as birds, and antenna axis divergence caused by wind and earthquakes etc. To cope with the changing received power, we applied automatic gain control (AGC). The gain of the MMW amplifier depends on the gate voltage of the HEMTs, which is automatically controlled so that the voltage of the output data signal is constant even though the input MMW power changes. The AGC function led to a received power margin of over 15 dBm.

Table 1. Specifications of 120-GHz-band wireless link.

Center frequency	125.000 GHz
Occupied bandwidth	116.5–133.5 GHz
Output power	10 dBm
Antenna	Cassegrain antenna
Antenna gain	48.8 dBi

To meet the 10GbE standard, we also measured the BER characteristics of the wireless link at a data rate of 10.3125 Gbit/s. We have achieved error-free transmission with a BER of 10^{-12} over a distance of 300 m. These results indicate that the 120-GHz-band wireless link can connect 10-Gbit/s optical fiber communication networks, such as OC-192 or 10GbE. It enables the use of components on the market for the O/E and E/O converters, baseband amplifier, and CDR circuits. Moreover, we can use HD-SDI signal multiplexers that have either OC-192 or 10GbE network interfaces, which reduces the development cost of the wireless link.

2.3 Wireless communication systems for multiplexed HDTV signals using i-Visto

2.3.1 OC-192 SONET/SDH-based wireless link system

We used the i-Visto gateway XG to multiplex HD-SDI signals over 10-Gbit/s fiber networks. The i-Visto (Internet video studio system for HDTV production) is an Internet-based video production-support system for professional use developed by NTT Laboratories. The i-Visto gateway converts between SDI/HD-SDI signals and IP streams [3]. The latest version, i-Visto gateway XG, supports various kinds of network interfaces including GbE, 10GbE, and OC-48/OC-192 POS (packet over SONET/SDH).

First, we investigated multiplexed wireless transmission systems that use the OC-48 and OC-192 network interfaces. Since OC-48 and OC-192 have higher reliability than the Ethernet network, they are commonly used to transmit HDTV material between TV stations. The setup for multiplexed wireless transmission of HD-SDI signals is shown in **Fig. 4(a)**. First, we used four i-Visto gateway XGs that support the OC-48 network interface. Each gateway converts the HD-SDI video stream from a video interface to IP packets in real time and transmits these packets via an OC-48 network interface. Four OC-48 signals are multiplexed by a SONET/SDH (synchronous optical network, synchronous digital hierarchy) multiplexer and sent over an OC-192 network. The OC-192 signals containing the 4-ch HD-SDI video stream are transmitted over the wireless link. In the receiver, the demodulated OC-192 signals are demultiplexed to OC-48 signals by the demultiplexer. The gateway in the receiver receives IP packets from a network interface, reconfigures individual digital video streams

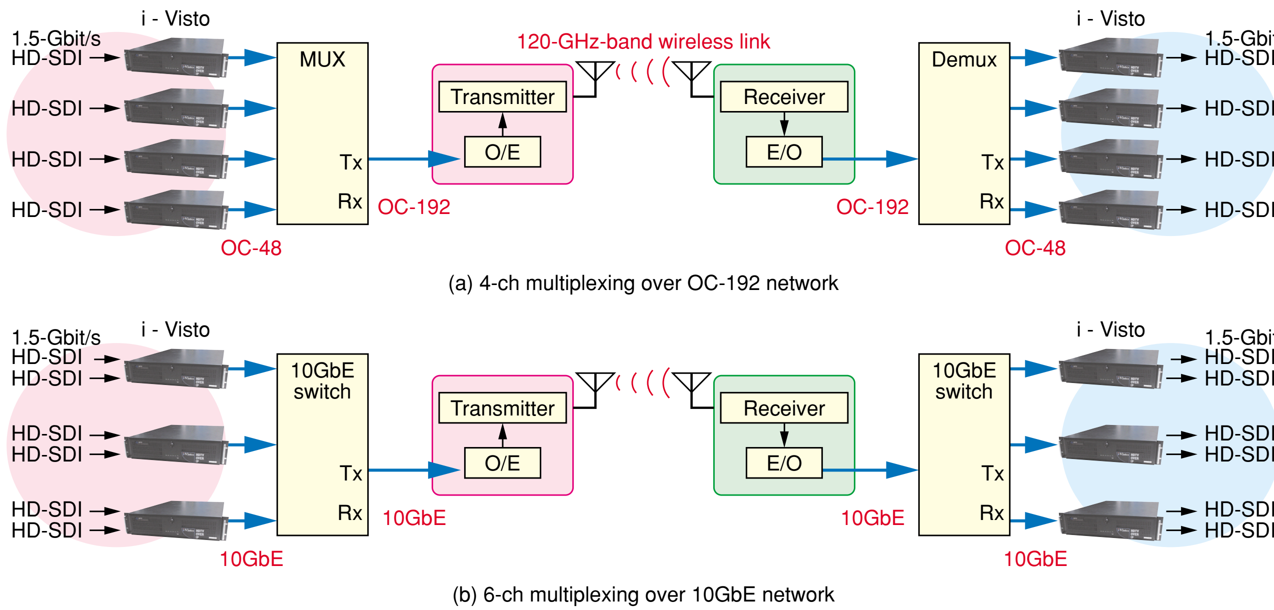

Fig. 4. Schematics of wireless links for multiplexed transmissions of uncompressed HD-SDI signals.

from them, and outputs them from corresponding video interfaces. At present, the 120-GHz band wireless link is a uni-directional communications system, so we invalidated the alarm detection and indication functions (layer 1) in SONET/SDH of the intermediate devices to prevent frames being discarded because of the absence of signals input to the Rx (receiver) port of the multiplexer (MUX) and LOS (loss of signal) detected because of the uni-directional communications. We chose Cisco HDLC-over-SONET/SDH [6] as the link-layer protocol from the POS family of protocols because it does not require any bidirectional negotiation between the sender and receiver gateways.

2.3.2 10GbE-based wireless link system

The wireless link system supporting an OC-192 network interface can transmit only four channels of HD-SDI signals, even though the transmission capacity of OC-192 is 9.953 Gbit/s. We have also developed a wireless link system that supports the 10GbE network interface in order to transmit a 6-ch-HD-SDI signal by using the i-Visto gateway XG. The schematic is shown in **Fig. 4(b)**. The i-Visto gateway XG can convert two HD-SDI video streams to IP packets and then multiplex these packets via a 10GbE network interface. The packets from three i-Visto XGs are multiplexed by a multi-port 10GbE layer 2 switch. Then six channels of HD-SDI signals are transmitted as 10GbE signals over the 120-GHz-band wireless link. In the receiver, each i-Visto gateway XG outputs two reconfigured video streams. We also optimized the protocol of the i-Visto gateway and the 10GbE switch. We invalidated the generation of local faults and remote faults provided in the reconciliation sublayer, which are the error detection and indication schemes defined in the 10GbE standard. And in layer 3, we used static IP addresses by controlling the address resolution protocol (ARP) tables and forwarding database explicitly in the gateways and intermediate 10GbE switches to avoid the need to execute bidirectional ARP operations. We implemented a traffic shaping function in the network interfaces of the i-Visto gateways to suppress burst traffic. This enabled us to keep the inter-packet gap larger than a certain amount of time in units of 5 ns. We set the inter-packet gap of each gateway so that the traffic rate did not exceed 3.3 Gbit/s to avoid exceeding the bandwidth capacity of 10GbE. This means that the multiplexed HDTV streams from three gateways never consume more than 9.9 Gbit/s.

3. Joint experiments with TV station

As part of an effort to promote the use of over-100-GHz MMWs, we have been conducting a joint experiment with Fuji Television Network, Inc. (Fuji TV) for multiplexed wireless transmission of uncompressed HD-SDI signals. We carried out public outdoor transmission trials at Odaiba in Tokyo in August 2005. A photograph of the experimental setup is

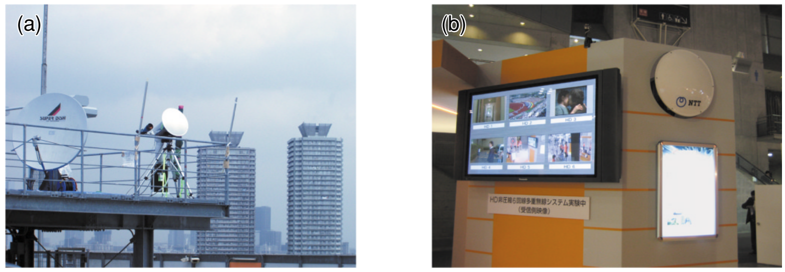

Fig. 5. (a) Public outdoor transmission trials for 2-ch uncompressed HD-SDI signals at Odaiba and (b) demonstration of 6-ch multiplexed wireless transmission of uncompressed HD-SDI signals at International Broadcast Exhibition (InterBee 2005).

shown in **Fig. 5(a)**. The receiver was set in the Fuji TV building, and the transmitter was placed on the roof of an adjacent building. The transmission distance was about 100 m, and there was a glass window between the transmitter and receiver. Error-free transmission at 10 Gbit/s was achieved, and two uncompressed HD-SDI signals in an OC-192 network were successfully transmitted over the 120-GHz-band wireless link even when rain was falling at a rate of 12.5 mm/hr.

We also demonstrated 6-ch multiplexed transmission of uncompressed HD-SDI signals over the 120-GHz-band wireless link at the International Broadcast Equipment Exhibition (InterBee 2005) held over three days in November 2005 at Makuhari. The 6-ch-HD-SDI signals were multiplexed over the 10GbE link using the experimental setup shown in Fig. 4(b). The transmitter and receiver were set in the Fuji TV booth about 4 m apart (**Fig. 5(b)**). In the demonstration, the wireless link was connected with a motion-control Camsat system developed by Fuji TV and transmitted six HDTV videos used as backgrounds in chroma key composition.

4. Future plans

The 120-GHz-band wireless link is scheduled to have its transmission distance extended by increasing the output power of the transmitter and the sensitivity of the receiver. This progress will be achieved mainly by improving the performance of the InP MMICs. The construction of bidirectional systems is also important. In the future, we plan to construct all-electronic systems using HEMT MMIC technologies [5], which should make the transmitter small and cost-effective.

We intend to promote the effectiveness of the 120-GHz-band wireless link in cooperation with internal and external users and begin standardization activities on the use of 120-GHz-band MMWs. We also plan to investigate other applications, such as non-contact ultrahigh-speed data transmission.

5. Conclusion

We have succeeded in demonstrating 6-ch multiplexed wireless transmission of uncompressed HDTV signals. The multiplexed wireless transmission was achieved using a combination of a 120-GHz-band wireless link and i-Visto gateways that convert HDTV signals to a video stream of IP packets and deliver them through OC-48 or 10GbE links. The 120-GHz-band wireless link uses photonic techniques to generate MMW signals, and we were successful in performing the world's first outdoor wireless transmission of OC-192 and 10GbE signals. This system is applicable to large-scale live relay broadcasting of HDTV programs in TV stations.

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