Non-mechanical Compact Optical Transceiver for Optical Wireless Communications

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1. Introduction

The advantages of optical communications as compared to radiowave (RF) communications include broader bandwidth, larger capacity, lower power consumption, more compact equipment, higher security against eavesdropping, better protection against interference, and the absence of regulatory restrictions (Hyde & Edelson, 1997). Moreover, the demand for high-data-rate transmission from spaceborne observation platforms is steadily increasing (Toyoshima, 2005a). Free-space optical (FSO) communications systems are expected to play an important role in providing such high-data-rate communications, and optical technologies for satellite networks are expected to revolutionize space system architecture (Chan, 2003). For terrestrial optical wireless communications, a transmitter with a 3 × 3 square array of vertical-cavity surface-emitting lasers (VCSELs) was evaluated in Parand et. al. (2003). Multiple-input multiple-output (MIMO) systems were presented based on optical code-division multiple-access (OCDMA), imaging diversity receivers, and white LEDs (Hamzeh et. al., 2004; Djahani et. al., 1999; Zeng et. al., 2009; Minh et. al., 2009). For long-range free-space laser communications, however, maintaining a line of sight between transceivers is particularly difficult because of the small divergence angle of the laser beams. Minimizing the requirements for the tracking system and ensuring the steady operation of the onboard optical terminal are therefore important for realization of commercial applications. FSO links are also well known for their susceptibility to adverse weather conditions such as cloud and fog, which pose great challenges to link availability. For terrestrial FSO links, RF links can be backed up to ensure continuous availability (Wu et. al., 2007).

Optical terminals for long-distance communications tend to have large mass because optical tracking systems require mechanically movable parts for coarse laser pointing and tracking. Reductions in mass, power, and volume can decrease interference with other missions on satellites. Non-mechanical movable architecture is extremely attractive for robust and lifelong operation of an optical terminal in orbit. The small satellite community still uses 9.6-kbps communication links by employing ham radio communications due to resource constraints in nano-class satellites (Nakaya et al., 2003; Miyashita et al., 2006). Compact terminals can be used in nano-class satellites that have a mass of the order of a few tens of kilograms. There is also a significant advantage concerning frequency-licensing problems faced by satellites, and in this regard optical frequency carriers will be of great use to the small satellite community. Research and development at National Institute of Information and Communications Technology (NICT) on FSO communications indicates that compact communications terminals will have good applicability in the future. NICT has developed a non-mechanical, compact optical terminal equipped with a two-dimensional laser array for space communications, and this paper considered its application toward indoor optical wireless communications.

In section 2, we propose the concept of a compact free-space laser communications terminal via the first implementation of an 8 × 8 VCSEL array. This optical system has no mechanically moving parts. This compact terminal can receive optical communications signals from multiple platforms and transmit multiple optical communications beams to the counter terminals. Such an optical system can therefore serve as a MIMO system. Section 3 presents the system analysis of the optical link budget for indoor optical wireless communications between an optical base station and distributed stations. Background noise is estimated during the daytime and eye safety is discussed with respect to the optical base station and the distributed stations.

2. Conceptual terminal design

2.1 System configuration

Figure 1 shows the configuration of the proposed compact laser communications transceiver. The laser beam from the counter terminal passes through the telescope lens, is reflected from the beam splitter, and is detected by the CCD sensor. The CCD sensor detects the direction of the counter terminal's line of sight, and one of the array lasers is selected according to the direction of the signal received by the CCD. A CCD with a pixel size equal to that of the XGA (1280 × 1024) is used. The centroid of the pixels is calculated in the computer, and the laser beam corresponding to the direction of the centroid is turned on. Figure 2 shows a photograph of the manufactured compact laser communications transceiver and control computer system. With this configuration, multiple inputs from multiple platforms are possible with the parallel laser spot detection processing, and MIMO configuration is also possible (Short et al., 1991).

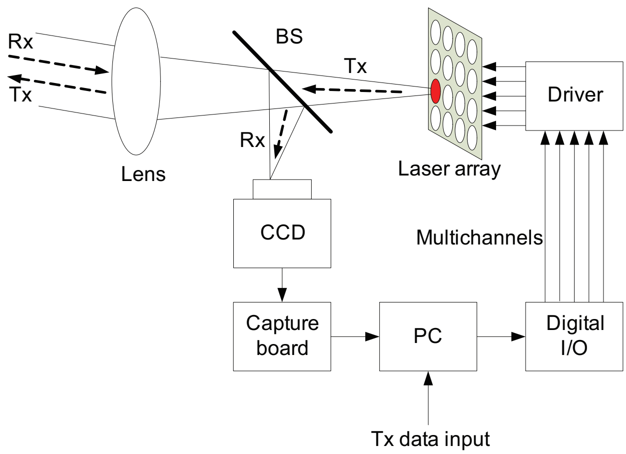

Fig. 1. Configuration of the proposed compact laser communications transceiver

2.2 Optical part of the transceiver

The laser beam is transmitted from the two-dimensional laser array through the beam splitter and telescope lens. The beam is selected by the centroid calculation in the computer. The beam divergence angle of the selected laser beam covers the angular interval between adjacent laser arrays (Cap et al., 2007). Two adjacent laser beams are turned on simultaneously to ensure that the laser transmission is not interrupted and to maintain a constant optical intensity at the counter terminal. Figure 3 shows the beam transmission configuration for a two-dimensional laser array. With this transmission method, the transmitted laser beam is not interrupted during the tracking of the counter terminal. Each laser beam is combined by an interval at the half width at half maximum (HWHM). Therefore, if the two adjacent laser beams are turned on simultaneously the optical intensity can be almost constant at the counter terminal.

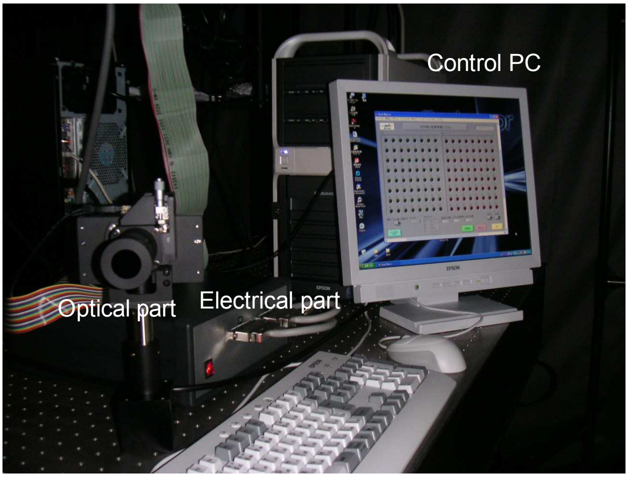

Fig. 2. Manufactured compact laser communications transceiver

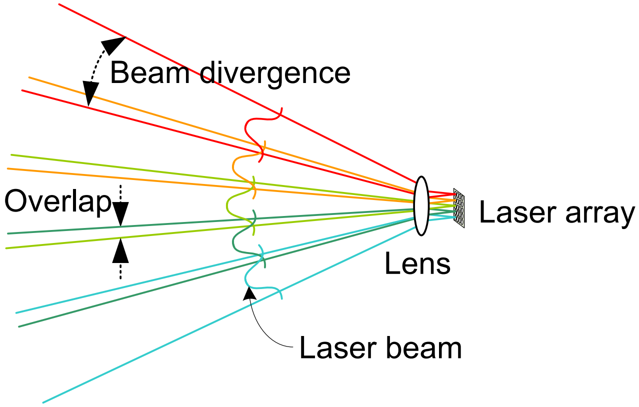

Fig. 3. Laser beam transmission method

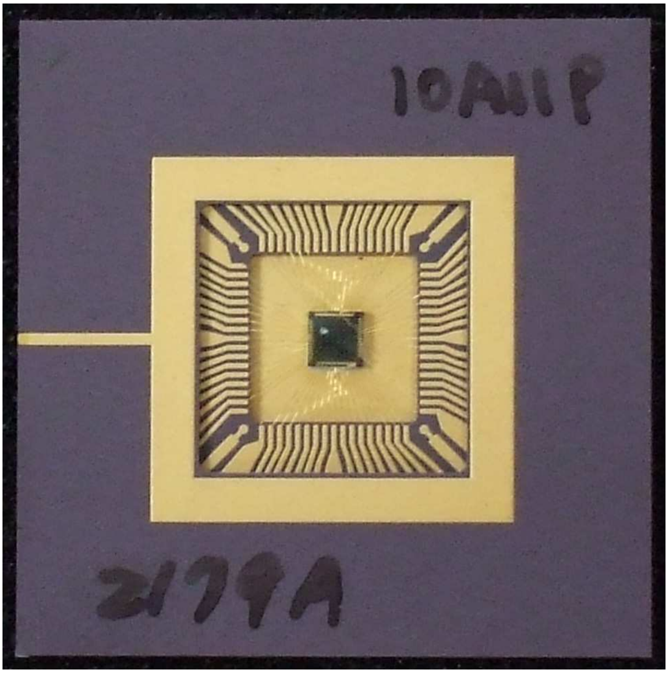

Fig. 4. 8 × 8 VCSEL array

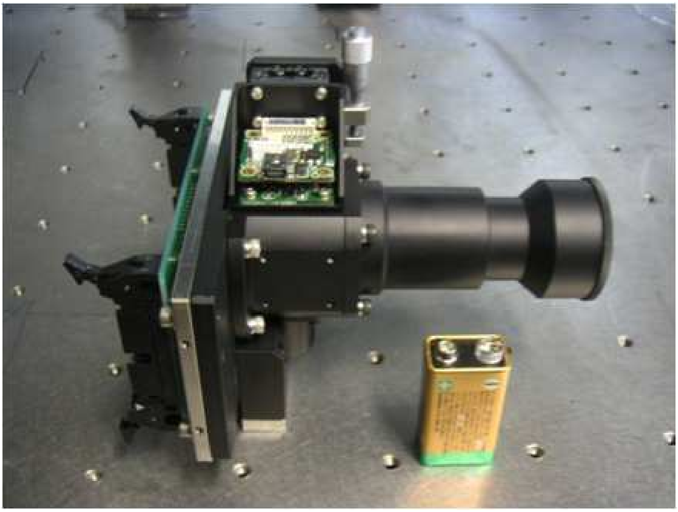

Fig. 5. Optical part of the compact laser communication transceiver

For the transmitter, we use an 8 × 8 VCSEL array, as shown in Figure 4, for the first evaluation model. VCSELs were chosen because they are easy to arrange in an array, there are no mechanical parts, and they are readily available. The maximum output power of one pixel is 4 mW at a wavelength of 850 nm, as shown in Table 1. The laser diode can be modulated at above 2.5 GHz. All the VCSELs could be turned on individually. The beam divergence for this evaluation model was designed to be 2 degrees for one VCSEL.

Fig. 6. Electrical part of the compact laser communication transceiver

Parameter	Value
Array number	64 (8 × 8)
Maximum output power of one pixel	4 mW
Wavelength	850 nm
Beam divergence angle	20-30 degrees
Minimum frequency response	2.5 GHz

Table 1. VCSEL array specifications

Figure 5 shows the optical part of the manufactured compact laser communications transceiver. The small telescope consists of nine lenses. The VSCEL is mounted at the end of the small telescope and the CCD sensor is mounted on the upper side of the telescope, as shown in Fig. 5. The size of the optical part of the telescope (lens mount) is 13.5 × 6 × 11 cm, power consumption is less than 10 W, and mass is 1 kg, as shown in Table 2. Commercial-off-the-shelf (COTS) transceivers usually have a tracking system and a COTS transceiver has power consumption of 20 W and mass of about 8 kg at 1.25 Gbps. Our system, however, has no mechanical tracking system; thus there is the potential of reduced mass, power, and volume in the proposed transceiver.

2.3 Electrical part of the transceiver

Laser beams in the VCSEL array are modulated according to the received laser spot extracted by the control computer system, as shown in Fig. 1. Two 32-channel digital I/O boards are installed and can transmit data at a rate of 25 Mbps. Figure 6 shows a photograph of the electrical part of the manufactured laser driver. The electrical part, as shown in Fig. 6, can drive 64 channels of the VCSELs by the selected signal from the digital I/O boards. The laser diode is driven at an average power of 2 mW by the driver electronics. The electrical part of the compact laser communications transceiver has mass of 3.1 kg, size of 27 × 26 × 10 cm, and power consumption of less than 10 W, as shown in Table 2.

Resource		Value
Optical part	Mass	1 kg
	Size (lens mount)	15 × 12 × 12 cm (13.5 × 6 × 11 cm)
Electrical part	Mass	3.1 kg
	Size	27 × 26 × 10 cm
	Power	< 10 W

Table 2. Compact laser communication transceiver resources

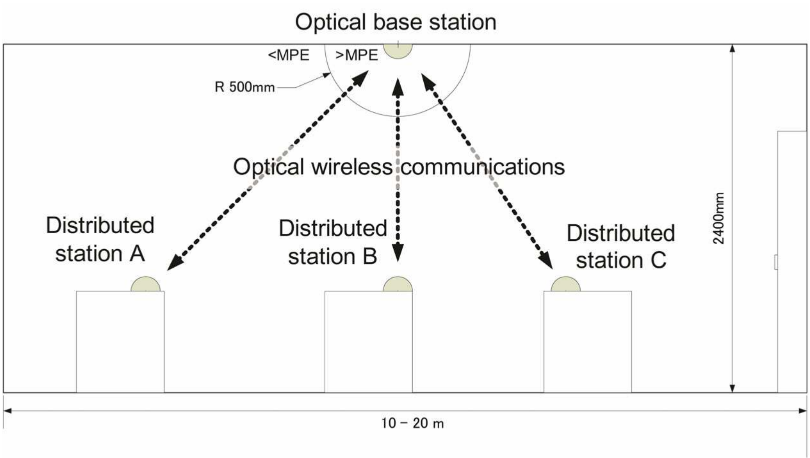

Fig. 7. Optical base station and distributed optical station layout

3. System analysis and experimental results

3.1 Link budget analysis

Table 3 summarizes the results of the link budget analysis for the proposed compact optical transceiver applied to indoor optical wireless communications. The optical link is designed to connect an optical base station on the ceiling with distributed optical terminals in a room, as shown in Fig. 7. The output laser power for a pixel of the VCSEL array is assumed to be 2 mW at 850 nm wavelength. The beam divergence angle is set at 0.33 rad for a single laser pixel for the full width at $1/e^2$ maximum (FWe^2M), and the angular coverage of the transmitter is 180° for a 8 × 8 array, which is sufficient to cover the number of distributed optical terminals in the room. The overlap of the beams is set to occur at the HWHM. The

beam pointing error can be considered as zero because the transmitting power can be doubled by turning on the adjacent two VCSELs simultaneously.
If stations A, B, or C simultaneously communicate with the base station, the spatial diversity can be performed by the different VCSEL lasers. If some stations can be within one laser beam, time-division multiple-access (TDMA), CDMA, or frequency-division multiple-access (FDMA) can be used for the communication scheme. By using these techniques, MIMO can be achieved with a single photo detector with the sufficient field of view (FOV) and appropriate optical filter. Figure 8 shows an example image of simultaneous two-target tracking measured by CCD. Figures 9 and 10 show the CCD pixels for simultaneous two-target tracking when one target is fixed and the other is oscillating at 5 and 10 Hz, respectively. These results show successful simultaneous two-target tracking, demonstrating the capability of MIMO for free-space laser communications.

Item	Unit	Value
TX power	mW	2.0
	dBm	3.0
Laser array pixel size	-	8x8
Beam diameter at telescope	μm	3.2
TX beam divergence	rad	0.33
Angular coverage	deg	180.0
TX optics loss	dB	-2.0
Wavelength	m	8.50E-07
Average pointing loss	dB	0.0
TX gain	dB	24.6
Distance	m	10.0
Space loss	dB	-163.4
Atmospheric transmission	dB	0.0
RX antenna diameter	cm	5.0
RX gain	dB	105.3
RX optics loss	dB	-2.0
RX power	dBm	-34.5
Data rate	bps	1.00E+09
Sensitivity (@BER of 10^{-6})	photons/bit	1000
	dBm	-36.3
Average margin for BER	dB	**1.9**
MPE	W/m^2	20.0
Margin for MPE	dB	0.4

Table 3. Link budget analysis between an optical base station on the ceiling and distributed optical terminals in a room

3.2 Background noise and eye safety

If we consider the FOV of about 10 degrees, the background level during the daytime becomes about -44 dBm by using an optical filter with 1 nm optical bandwidth and 5 cm aperture diameter. In this case, the signal-to-noise ratio (SNR) can be about 10 dB for the received level at a BER of 10^{-6}, as shown in Table 3. Due to the background, a detector array with FOV of 10 degrees should be used to achieve a 1 Gbps data rate. Pointing therefore needs to be achieved at the receiver.

The link distance is assumed to be 10 m from the optical base station on the ceiling to the distributed optical stations. If we use on-off-keying (OOK) non-return-to-zero (NRZ) data transmission with a receiving aperture with a 5 cm diameter in the proposed system, the link margin will be 1.9 dB at a data rate of 1 Gbps with BER of 10^{-6}. In order to keep the eyes safe from laser beam radiation, the irradiance from the optical base station should be lower than the maximum permissible exposure (MPE) beyond a distance of 50 cm. On the other hand, the laser beam in the distributed stations close to the users can be never transmitted until when the laser beam from the optical base station is received as the protocol. If the laser beam is received by the distributed optical stations it will not contact the human eyes. Therefore, by this procedure the eye safety can be preserved in the distributed optical stations close to the users.

As shown in Table 3, the proposed non-mechanical method can be applied to terrestrial free-space laser communications. If the proposed terminal can be greatly compacted, mobile users can use the high-data-rate optical link without a mechanical tracking system on the ground, like a digital camera. Setting up the optical transceivers is easy and their installation is uncomplicated. In the future, applicable fields for the optical transceivers will include not only satellite communications but also high-speed cell phone communications, wireless LAN, mobile communications, and building-to-building fixed high data rate communications with no difficulties. The reliability of VCSELs, however, must be examined in the future based on the given environment.

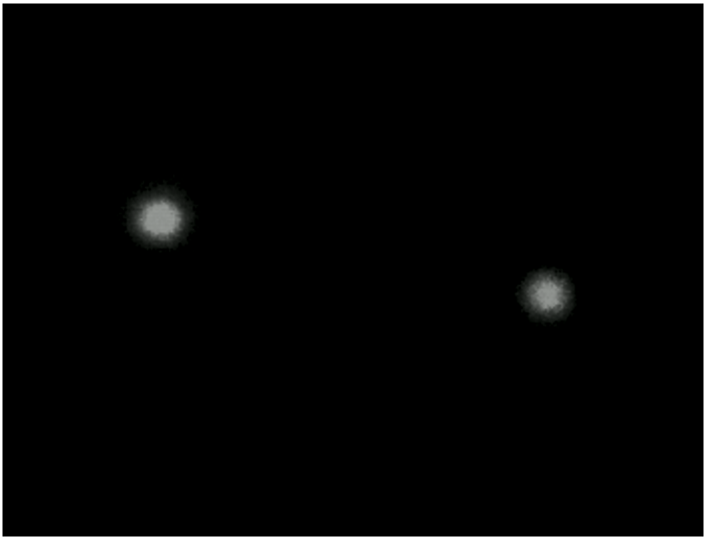

Fig. 8. Example of simultaneous two-target tracking measured by CCD

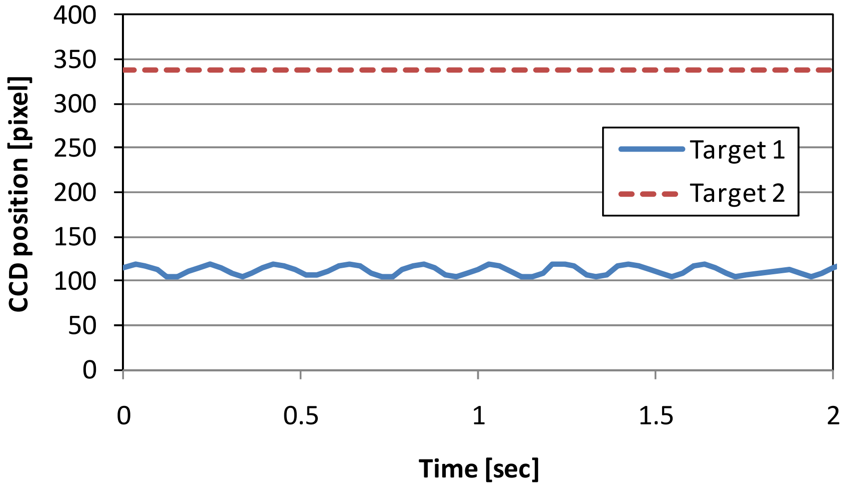

Fig. 9. CCD pixels for simultaneous two-target tracking when one target is fixed and the other is oscillating at 5 Hz

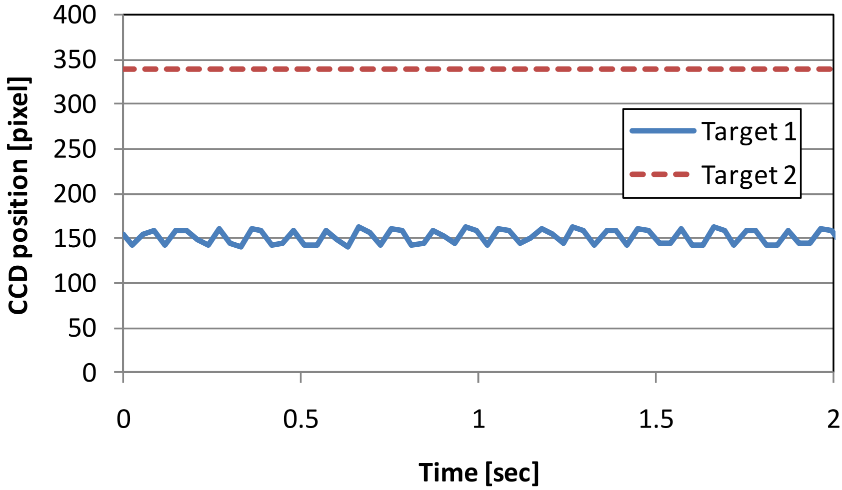

Fig. 10. CCD pixels for simultaneous two-target tracking when one target is fixed and the other is oscillating at 10 Hz

3.3 Future issues

The system proposed in this paper was developed for space communications but applied for indoor networks. Indoor optical wireless systems face stiff competition from future WiFi (802.11n) and 3GPP evolutions (IMT-Advanced), which will have data rates respectively exceeding 300 Mbps and 100 Mbps. The Gbps-class optical indoor wireless system may, however, play an interesting role in high data transmission and supplementing for drawbacks of frequency and bandwidth allocation and interference problems between RF and optical systems. Optical wireless systems should not compete with each other. Standardization efforts will be carried out with respect to the supplementing and also to ensure Gbps-class optical wireless interfaces on future user devices.

4. Conclusion

We have presented a non-mechanical and highly compact optical transceiver. A VCSEL array is used in the transceiver, and the laser pixel turned on depends on the direction of the counter terminal from which the CCD receives a signal. The mass, volume, and power of the proposed system can be reduced because it contains no mechanically movable structures. This study used an 8 × 8 VCSEL, which, to the best of our knowledge, is the first such implementation. The VCSEL number can be increased for improving the number of counter terminals but the MPE must be reduced, which is the tradeoff in the system design, and a novel protocol was proposed for eye safety. A simultaneous two-target tracking test was performed and demonstrated the capability of MIMO for free-space laser communications. As there are no regulatory restrictions on the use of the optical frequency, the proposed compact laser communications transceiver will be useful not only for satellites but also terrestrial optical wireless communications in future applications.

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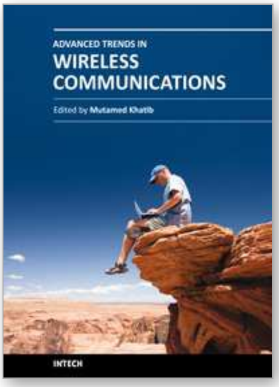

Advanced Trends in Wireless Communications

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Physical limitations on wireless communication channels impose huge challenges to reliable communication. Bandwidth limitations, propagation loss, noise and interference make the wireless channel a narrow pipe that does not readily accommodate rapid flow of data. Thus, researches aim to design systems that are suitable to operate in such channels, in order to have high performance quality of service. Also, the mobility of the communication systems requires further investigations to reduce the complexity and the power consumption of the receiver. This book aims to provide highlights of the current research in the field of wireless communications. The subjects discussed are very valuable to communication researchers rather than researchers in the wireless related areas. The book chapters cover a wide range of wireless communication topics.