Design of RoF-based Fiber-Wireless System for THz-Band 6G Indoor Network

Minkyu Sung[(1)], Sooyeon Kim[(1)], Eon-Sang Kim[(1)], Sang-Rok Moon[(1)], Mugeon Kim[(1)], IL-Min Lee[(1)], Kyung Hyun Park[(1)], Joon Ki Lee[(1)], Seung-Hyun Cho[(1)]

[(1)] Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea. (smk9620@etri.re.kr)

Abstract *We experimentally demonstrate RoF-based fiber-wireless seamless system for THz-band 6G indoor network. Based on the theoretical analyses and experimental results, we present design issues in RoF-based fiber-wireless system. ©2022 The Author(s)*

Introduction

As the deployment of 5G network infrastructure are being rolled all over the world, our focus is shifting to development of 6G wireless communications [1]. To meet the ever-increasing expectations for higher data rates and lower latency, "Terahertz" frequencies above 100 GHz are an attractive resource [2]. While a rich spectral resource offers the opportunities to achieve remarkable leaps in terms of peak data-rates, latency and more, there are several technical challenges arising from the fundamental physical constraints on the THz band [3]. A large propagation loss occurs in THz frequency because the free-space path loss (FSPL) of the electromagnetic wave is proportional to the square of the carrier frequency as well as the propagation distance. Further, THz communication suffers greater link losses when penetrating blockages such as low-emissivity window. Accordingly, the coverage of networks using THz frequencies would be reduced compared to the current mobile services based on ultra-high frequency or millimeter-wave (mmWave) band, and THz communications are expected to be mainly served on indoor networks rather than outdoor environments. In addition, an increase in the number of antenna-sites required is inevitable, and a simplified configuration of antenna-site would be preferred.

Fiber-wireless seamless network based on analog radio-over fiber (RoF) technology is attractive solution that provides simple and cost-effective configuration at antenna-sites for 6G indoor services. Compared to digital photonic link to support mobile transport network, analog transmission of RoF technology gives the opportunity to eliminate high implementation complexity and cost in antenna-site incurred digital to analog conversion procedure [4]. Further, it is well known that the analog RoF transmission has great potentials to resolve bandwidth bottleneck in mobile transport link [5, 6]. Using a photonic-assisted carrier generation based on optical heterodyne, we can eliminate complex electrical signal up-conversion [7].

Previously, many research groups have been demonstrated the fiber-wireless systems in mmWave band. These works have presented the potential of fiber-wireless system with simple and cost-effectiveness for implementing antenna-sites [7-10]. Unfortunately, however, there are no reports of the comprehensive study on transmission performance of fiber-wireless system operating at THz frequencies and no example of verifying the validity of the theoretical analysis through the actual THz wireless transmission experiment using mobile signals.

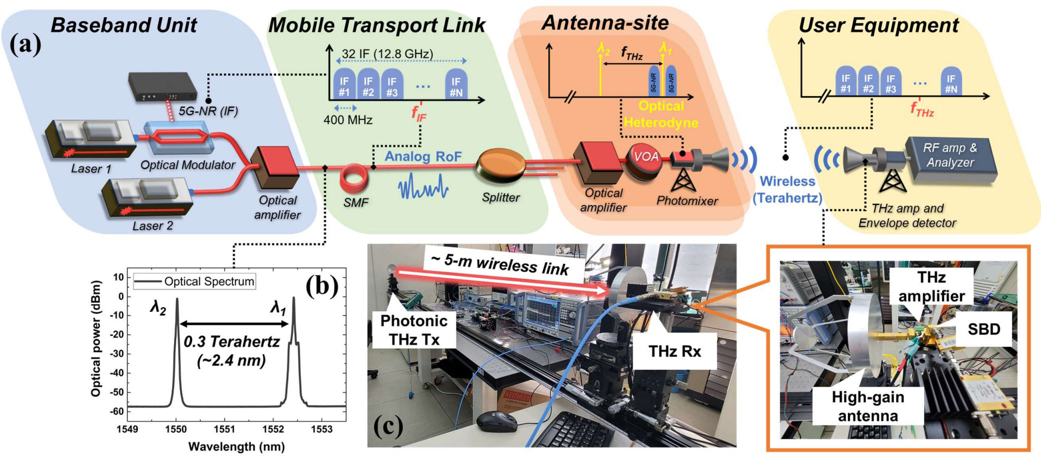

Fig. 1: RoF-based fiber-wireless system for THz-band 6G indoor network. (a) Experimental setup (b) Optical spectrum (c) Photograph of experimental setup

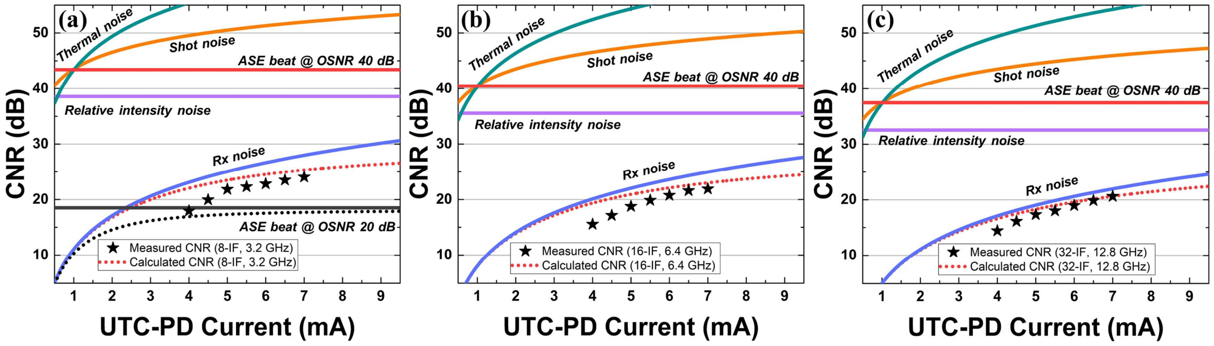

Fig. 2: CNR analyses of RoF-based fiber-wireless links in 0.3 THz frequency using 5G-NR mobile signal aggregated with multiple IFs. Solid lines are theoretically calculated CNRs for various noise sources. (a) 8 IF (b) 16 IF (c) 32 IF

In this paper, we experimentally demonstrate the THz-band indoor network using analog RoF-based fiber-wireless seamless configuration. To provide the guideline in designing RoF-based fiber-wireless link, we analyse noise contributions considering quality of analog optical link. Furthermore, the expected wireless coverage of THz indoor network is investigated through the theoretical analyses and experimental results taking into account the impact of FSPL. For a more practical solution, the lens-less experimental configure is used for free-space transmission of THz signal. Using developed high-gain antenna and RF amplifier operating in THz frequency, the FSPL is effectively compensated, and 5-m wireless transmission of aggregated 32-intermediate frequency (IF) carriers on the 0.3 THz link is successfully demonstrated satisfying minimum required performance for 16-QAM.

Experimental setup and results

Figure 1 (a) represents the concept of RoF-based fiber-wireless system for THz-band indoor service and experimental setup to confirm technical feasibility of proposed system. Two commercial C-band laser diodes (LDs) are used to generate optical carriers in which separated to 2.4 nm in wavelength (~300 GHz). An optical carrier from LD1 is modulated with mobile signal by using a zero-chirped dual-drive Mach-Zehnder modulator with a 40-GHz bandwidth; the other carrier from LD2 is directly combined with a modulated optical carrier by a 50:50 optical coupler. As mobile signal, we generated 5G-new radio (5G-NR) waveform with a bandwidth of 400 MHz. Multiple mobile baseband signals are aggregated as a form of IF carrier. We set the number of IF carriers to 8, 16 and 32, occupying the RF spectrum of 3.2, 6,4 and 12.8 GHz, respectively. The optical carriers are transmitted over 1-km of SMF as mobile transport link. For THz wave generation, the uni-traveling carrier photodiode (UTC-PD) is used in which this photomixer performs optical heterodyne. To provide a sufficiently large input optical power for photomixer, Erbium-doped fiber amplifiers (EDFA) are utilized. At the receiver, the envelope detection is performed using GaAs Schottky barrier diode (SBD) module with sensitivity of 1900 V/W. And then, RF amplifier with 40 GHz bandwidth and noise figure of 7 dB performs signal amplification, after that, error vector magnitude (EVM) is analysed by off-line digital signal processing using MATLAB.

One of the important parameters in designing RoF-based mobile transport network is an achievable carrier-to-noise ratio (CNR) [11]. Therefore, we investigate the CNR characteristics on RoF-based fiber-wireless system over 0.3 THz wireless link as in Figs. 2. The quality of analog RoF link is calculated considering the undesired optical power fluctuations caused by optical components degrade transmission performance and could be categorized to thermal noise, shot noise, and laser relative intensity noise (RIN). In addition, amplified spontaneous emission (ASE) noise induced by the EDFA that is used to obtain sufficient THz output power from UTC-PD is also analysed as one of optical white noise sources. The ASE noise degrades the OSNR and appears in the electrical domain after photomixing. There are two ASE noise contribution in THz domain; ASE-ASE beat noise and signal-ASE beat noise that is considered a major performance limiting factor in photonic THz communications [12].

Unlike the conventional optical transmission networks, the RoF-based fiber-wireless system requires a sufficiently large received optical power to UTC-PD, as a result, thermal noise and shot noise is negligible. Owing to mature laser manufacturing technology, even a low-cost commercially available LD can provide RIN characteristic less than -150 dB/Hz, which is shown lower noise level compared to that from the receiver having a noise equivalent power of 16.5-pW/Hz$^{0.5}$ in this work. Typically, the transmission performance is mainly dominant at the reception side. On the other hand, it is observed at OSNR of 20 dB that ASE beat noises dominantly limit the CNR as shown in Fig. 2 (a). Therefore, it is worth

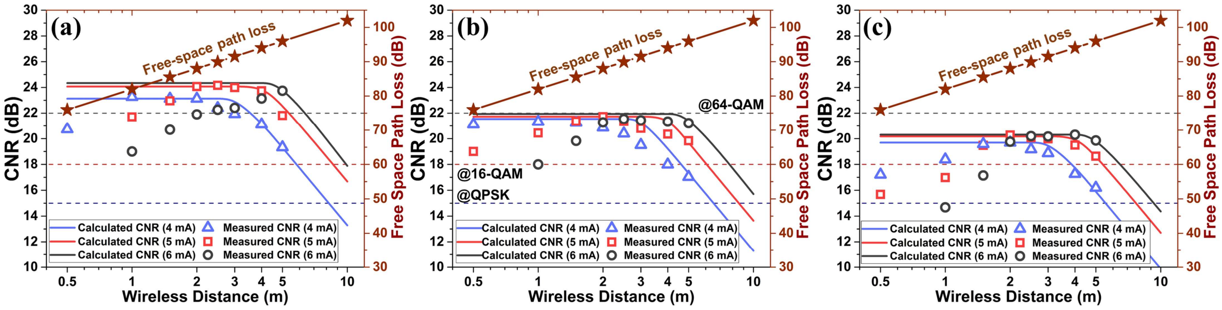

Fig. 3: CNR performances for different UTC-PD currents as a function of wireless distance in THz wireless communication. Solid lines are theoretically calculated achievable CNRs taking into account the free-space path loss (a) 8 IF (b) 16 IF (c) 32 IF

noting that poor OSNR condition could be constraint to transmission performance, and we should consider OSNR performance when designing RoF-based fiber-wireless system [12].

To verify the noise contribution analyses, we configure wireless back-to-back condition for the experiments; two WR 3.4 waveguided horn antennas with 26-dBi gain were placed at a distance of 20-mm from each other. We measured EVM performances as a function of UTC-PD current for the 8, 16 and 32 IFs of 5G-NR over 0.3 THz wireless link. Considering the relationship between CNR and EVM as

$$CNR\ (\mathrm{dB}) = -20\log_{10}(EVM/100\%) \qquad (1)$$

, we obtain CNR performances of THz links in RoF-based fiber-wireless system and they have good agreements with theoretically calculated CNRs. Considering required CNR as defined in technical specification of 3GPP for different modulation format (64-QAM: 22 dB, 16-QAM: 18 dB, QPSK: 15 dB), the CNRs greater than 18 dB are achieved for all modulation formats at the UTC-PD current of 7-mA [11, 13].

From the study on CNR characteristics of RoF-based fiber-wireless system, we confirmed the major performance limiting factor is typically the white noise generated by the receiver. Therefore, we can infer a major challenge of RoF-based fiber-wireless system for 6G indoor network is FSPL in THz frequency, which are relatively large compared with microwave and mmWave bands. Previously, many related experiments about THz wireless transmission used several lenses to compensate for wireless link loss, such as FSPL [14]. However, using lenses is not a rather practical configuration. In Figs. 3, we demonstrate the THz wireless transmission with lens-free experimental configuration. To compensate for propagation loss, we developed a high-gain antenna of 40-dBi and an RF amplifier operating a THz frequency with a gain of 16 dB, and implemented them in the experiments as shown in Fig. 1 (c).

The measured CNRs show that after 5-m wireless transmission, 8 IF satisfies the required performance of 64-QAM. The results of 16 IF and 32 IF also show that even with 16-QAM, a network coverage of 5-m can be achieved at a frequency of 0.3 THz. On the other hand, at the wireless transmission of 2.5-m or less, it is observed that CNR performances deteriorates. Also, the greater THz output power, the more noticeable the performance degradation is. This is because nonlinear distortions induced by the inherent nonlinearities of THz amplifier and envelope detector cause severe performance degradation [15]. A high peak-to-average power ratio characteristic of multi-IFs 5G-NR signal, where each IF is modulated by orthogonal frequency division multiplexing, also would increase nonlinear distortions [16]. We also derive the achievable CNR performance considering FSPL impact to provide the design guideline for the THz-band indoor service. As shown in Fig. 3 (a), we can expect that 10-m wireless transmission of 8-IF carriers would be allowed for 16-QAM. On the other hand, for 32-IF transmission, there is no modulation format that meets the CNR requirement at 10-m wireless coverage. Nevertheless, the main performance limiting factor is FSPL, so we can expect to achieve 16-QAM with 10-m and more wireless coverage at 32 IF transmission by compensating for the FSPL with beam steering techniques or a high-power amplifier in photonic THz transmitters [17, 18].

Conclusions

In this paper, THz-band indoor network using RoF-based fiber-wireless system is demonstrated. Based on theoretical analyses and experimental results, we present the guideline to implement the RoF-based fiber-wireless system. The successful demonstration of multiple IFs of 5G-NR transmission over 0.3 THz link shows that the potential of RoF-based fiber-wireless system for 6G indoor network using THz frequency.

Acknowledgements

This work was supported by the ETRI grant funded by the Korean government. [22ZH1110, Study on 3D communication technology for hyper-connectivity].

References

[1] F. Tariq, M. R. A. Khandaker, K.-K. Wong, M. A. Imran, M. Bennis, M. Debbah, "A speculative study on 6G," *IEEE Wireless Communications*., vol. 27, pp.118–125, Aug. 2020, **DOI:** 10.1109/MWC.001.1900488

[2] H.-J. Song, "Terahertz Wireless Communications: Recent Developments Including a Prototype System for Short-Range Data Downloading," *IEEE Microwave Magazine,* vol. 22, no. 5, pp. 88-99, May. 2021, **DOI:** 10.1109/MMM.2021.3056935

[3] T. Kawanishi, "THz and Photonic Seamless Communications," *Journal of Lightwave Technology*, vol. 37, no. 7, pp. 1671–79, Feb. 2019, **DOI:** 10.1109/JLT.2019.2897042

[4] D. Milovančev, N. Vokić, F. Karinou, and B. Schrenk, "Simplified Coherent Receiver for Analogue Radio Transmission Over High Optical Budgets", *Journal of Lightwave Technology*, vol. 39, no. 24, pp. 7672–7681, Dec. 2021, **DOI:** 10.1109/JLT.2021.3085517

[5] M. Sung, J. Kim, E.-S. Kim, S.-H. Cho, Y.-J. Won, B.-C. Lim, S.-Y. Pyun, H. Lee, J. K. Lee, and J. H. Lee, "RoF-based radio access network for 5G mobile communication systems in 28-GHz millimeter-wave," *Journal of Lightwave Technology,* vol. 38, no. 2, pp. 409–420, Jan. 2020, **DOI:** 10.1109/JLT.2019.2942636

[6] S. Ishimura, H-Y. Kao, K. Tanaka, K. Nishimura, R. Inohara, and M. Suzuki, "Multi-IF-over-fiber transmission using a commercial TOSA for analog fronthaul networks aiming beyond 5G," *Optics Express*, vol. 29, no. 2, pp. 2270–2278, Jan. 2021, **DOI:** https://doi.org/10.1364/OE.414714

[7] P. T. Dat, F. Rottenberg, A. Kanno, K. Inagaki, J. Louveaux, N. Yamamoto, and T. Kawanishi "132 Gb/s 3×3 full MIMO fiber–wireless seamless system in w band using WDM/PDM RoF transmission," *in proceeding European Conference on Optical Communications (ECOC)*, Dec. 2020, **DOI:** 10.1109/ECOC48923.2020.9333373

[8] S. Jia, L. Li, Y. Fu, L. Oxenløwe, and H. Hu, "DMT-16QAM photonic-wireless link in W-band enabled by an integrated MLL chip," *in proceeding European Conference on Optical Communications (ECOC)*, Dec. 2020, **DOI:** 10.1109/ECOC48923.2020.9333152

[9] N. Argyris, G. Giannoulis, K. Kanta, N. Iliadis, C. Vagionas, S. Papaioannou, G. Kalfas, D. Apostolopoulos, C. Caillaud, H. Debrégeas, N. Pleros, and H. Avramopoulos, "A 5G mmWave fiber-wireless IFoF analog mobile fronthaul link with up to 24-Gb/s multiband wireless capacity," *Journal of Lightwave Technology*, vol. 37, no. 12, pp. 2883–2891, Jun. 2019, **DOI:** 10.1109/JLT.2019.2897109

[10] R.-K. Shiu, S.-J. Su, Y.-W. Chen, Q. Zhou, J. Chiu, G.-M. Shao, L. Zhao, P.-C. Peng, and G.-K. Chang., "RF fading circumvention using a polarization modulator for supporting W-band RoF transport from 85 to 95 GHz," *in proceeding Optical Fiber Communications Conference and Exhibition (OFC)*, 2020, **DOI:** https://doi.org/10.1364/OFC.2020.Th2A.43

[11] H. S. Chung, S.-H. Cho, C. Han, S. Lee, J. C. Lee, and J. H. Lee, "Design of RoF based mobile fronthaul link with multi-IF carrier for LTE/LTE-A signal transmission," *in proceedings International Topical Meeting on Microwave Photonics (MWP) and Asia-Pacific Microwave Photonics Conference (APMP)*, 2014, pp. 303–306. **DOI:** 10.1109/MWP.2014.6994559

[12] M. Sung, S.-R. Moon, E.-S. Kim, S. Cho, J. K. Lee, S.-H. Cho, T. Kawanishi, and H.-J. Song, "Design Considerations of Photonic THz Communications for 6G Networks," *IEEE Wireless Communications*, vol. 28, no. 5, pp. 185–191, Oct. 2021, **DOI:** 10.1109/MWC.001.2100002

[13] "User equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone," *3rd Generation Partnership Project*, Sophia Antipolis, France,3GPP TS 38.101-1 v. 15.3.0, Rel. 15, Sep. 2018.

[14] X. Li, J. Yu, K. Wang, M. Kong, W. Zhou, Z. Zhu, C. Wang, M. Zhao, and G.-K. Chang, "120 Gb/s Wireless Terahertz-Wave Signal Delivery by 375 GHz-500 GHz Multi-Carrier in a 2 × 2 MIMO System," *Journal of Lightwave Technology*, vol. 37 no. 2, pp. 606–611, Jan. 2019, **DOI:** 10.1109/JLT.2018.2862356

[15] T. Harter, C. Füllner, J. N. Kemal, S. Ummethala, J. L. Steinmann, M. Brosi, J. L. Hesler, E. Bründermann, A.-S. Müller, W. Freude, S. Randel, and C. Koos, "Generalized Kramers–Kronig receiver for coherent terahertz communications," *Nature Photonics*, vol. 14, no. 10, pp. 601–606, Sep. 2020, **DOI:** https://doi.org/10.1038/s41566-020-0675-0

[16] M. Sung, C. Han, S.-H. Cho, H. S. Chung, and J. H. Lee, "Improvement of the transmission performance in multi-IF-over-fiber mobile fronthaul by using tone-reservation technique," Optics Express, vol. 23, no. 23, pp. 29615–29624, Nov. 2015. **DOI:** https://doi.org/10.1364/OE.23.029615

[17] J. Tebart, P. Lu, T. Haddad, S. Iwamatsu, J. Lackmann, J.L. Fernandez-Estevez, and A. Stöhr, "Mobile Terahertz 6G Communications Enabled by Integrated Photonic-Assisted Beam Steering Antennas", *in proceeding European Conference on Optical Communications (ECOC)*, Sep. 2021, **DOI:** 10.1109/ECOC52684.2021.9605939

[18] K. Eriksson, I. Darwazeh, and H. Zirath, "InP DHBT distributed amplifiers with up to 235-GHz bandwidth," *IEEE Transactions on Microwave Theory and Techniques*, vol. 63, no. 4, pp. 1334–1341, Apr. 2015. **DOI:** 10.1109/TMTT.2015.2405916