Simply configured Radio on Fiber link yielding positive gain for mobile phone system

Junji Higashiyama^{1a)}, Yoshiaki Tarusawa¹, and Masafumi Koga²

¹ Research Laboratories, NTT DOCOMO, INC.,

3–6 Hikarino-oka, Yokosuka-shi, Kanagawa 239–8536, Japan

² Department of Electrical and Electronic Engineering, Faculty of Engineering,
Oita University, 700 Dannoharu, Oita-shi, Oita 870–1192, Japan

a) higashiyamaj@nttdocomo.com

Abstract: This paper proposes a simple and cost-effective configuration for an analogue Radio on Fiber (RoF) link without any amplifier comprising driver and receiver circuits with stubbed microstrip lines. This simple configuration yields a gain of +4 dB with a spurious free dynamic range (SFDR) of 58 dB. An adjacent carrier leakage ratio (ACLR) of less than –63 dB and an error vector magnitude (EVM) of less than 1% are also achieved. These results satisfy the specifications given in the technical standard published by the third generation partnership (3GPP).

Keywords: radio on fiber, inter modulation, impedance matching, spurious free dynamic range

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

References

- [1] D. Astely, E. Dahlman, G. Fodor, S. Parkvall and J. Sachs: IEEE Commun. Mag. **52** [7] (2013) 154. DOI:10.1109/MCOM.2013.6553692
- [2] LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception, 3rd Generation Partnership Project, 3GPP TS 36.104 V8.13.0 (2012).
- [3] LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception, 3rd Generation Partnership Project, 3GPP TS 36.101 V8.21.0 March 2013.
- [4] LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) conformance testing, 3rd Generation Partnership Project, 136 141 V10.11.0 (2013).
- [5] R. C. Williamson and R. D. Esman: J. Lightwave Technol. **26** (2008) 1145. DOI:10.1109/JLT.2008.923627
- [6] D. Fisher and K. Burden: IEEE Microw. Mag. **15** [1] (2014) 115. DOI:10.1109/MMM.2013.2288837

1 Introduction

The demand for high-throughput mobile communications has increased in recent years. To meet this demand, radio access technologies especially in utilizing multi-band radio frequencies, have been continually developed. These are well known as the third generation partnership project (3GPP) technical standards based on the Orthogonal Frequency Division Multiple Access (OFDMA) and Multiple Input and Multiple Output (MIMO) multiplication [1, 2, 3, 4]. This multi-band radio access technology requires a large number of antenna elements and feeder lines in the construction of antenna systems for radio base stations.

An optical fiber is lighter and has a smaller diameter than a coaxial cable. If an optical fiber can be applied to an antenna system as the feeder line instead of a coaxial cable, the design will become slimmer and more compact. Although the optical transmission loss of only the optical fiber is low, a radio-on-fiber (RoF) analogue link, which employs a direct intensity modulation scheme for a laser diode (LD), generally has a higher level of transmission loss than the coaxial cable due to the electrical-to-optical (E/O) and optical-to-electrical (O/E) conversion losses. The transmission gain for this type of RoF analogue was reported to be -15 to -30 dB [5, 6].

In this paper, passive impedance matching networks are applied to LD and photo diode (PD) circuits to improve the RoF transmission characteristics including the gain, and experimental results are presented to show the feasibility.

2 Design of driver and receiver circuits

Fig. 1 shows the RoF link comprising the driver circuit, receiver circuit, and a 100-m single mode optical fiber. The driver circuit includes a 1.55 micron distributed-feedback (DFB) LD, a microstrip matching network, and a choke coil for the bias. The receiver circuit includes an InGaAs p-i-n PD, a microstrip matching network and a choke coil for the bias. The LD is directly modulated by a microwave signal at the bias current of 50 mA. The circuits between the RF analogue modulation input and LD, and between the PD and RF output are configured by pi-section distributed line matching networks to match the impedance at the target frequency band.

In the microwave frequency range, the impedance of the LD is lower than 50 ohms. In the driver circuit, the matching network comprises a stubbed microstrip line to be tuned at the frequency of 1.5 GHz. On the other hand, the output impedance of the p-i-n PD is higher than 50 ohms in the microwave frequency range. In the receiver circuit, the matching network is directly connected to the p-i-n PD with the 50 ohm transmission line through a capacitor to cut the DC bias. The matching network comprises a stubbed microstrip line, which is the same as in the network for the driver circuit. The reflection coefficients in the driver and receiver circuits were measured and are less than -15 dB at the target frequency.

Fig. 1. Configuration for experimental RoF link.

3 Experimental results

Dynamic responses were measured to evaluate the applicability of the proposed construction to the transmission of mobile radio signals between the RF input and output ports shown in Fig. 1. The responses are shown in Fig. 2. The third-order intermodulation (IM3) characteristics were measured using the two tone test method that employed the carrier frequencies of 1.5 GHz and 1.495 GHz. The intercept point (IP) at the output was read out from the cross point of the fundamental and IM3 component lines. The noise level was evaluated at the bandwidth of 10 MHz.

The transmission gain was measured between the RF input and output ports under the condition of a 50-ohm system. The maximum transmission gain achieved is +4.2 dB with the driver and receiver circuits, while the gain without the matching network is −10 dB. Thus, the effect of the impedance matching is a 14-dB increase in gain. On the other hand, the IP and spurious free dynamic range (SFDR) with the driver and receiver circuits are +20 dBm and 58 dB, and exhibit degradation levels of −2 dB and −4 dB, respectively, compared to the response characteristics of the driver and receiver circuits without the matching network.

The transmission gain of the analog RoF link generally depends on the modulation gain of the LD optical intensity, the optical fiber loss, the quantum efficiency of the PD, and the impedance mismatching at the driver and receiver circuits. The proposed configuration of the RoF link resolves the impedance mismatching at the driver and receiver circuits by applying the pi-section distributed line matching networks. The reduction in the loss due to the impedance mismatching contributes to the transmission characteristics with a positive gain. The achieved positive gain is more effective and important to the transmission characteristics of this RoF link considering the design of the level diagrams for the equipment for the transmitter and receiver.

To increase the information transmission rate, recent mobile radio access techniques implement OFDMA with multiple QAM modulation schemes such

as 16QAM and 64QAM. This trend increases the peak to average power ratio (PAPR) of the envelope of the radio transmission signal to a level higher than that of conventional techniques. For example, the PAPR of the OFDMA signal based on LTE employed in 3GPP Rel. 8 is approximately 4-dB higher than that for the W-CDMA signal employed in 3GPP Rel. 99 at the complementary cumulative distribution function (CCDF) of 0.01%. A radio transceiver comprising linear circuits requires no distortion, i.e., a wider SFDR. In this study, the OFDMA signal defined in Table I is transmitted using the RoF link shown in Fig. 1 [4].

Fig. 2. Dynamic responses when using pi-section distributed line matching network at frequency of 1.5 GHz band.

Table I. Transmission signal for measuring characteristics

3GPP Release*	Release 8
Multiple access	OFDMA for LTE downlink
Configuration of physical channels	E-UTRA Test Model 3.1
Channel bandwidth	20 MHz
Number of resource blocks	100
Modulation of physical resource block	64QAM

*Technical specifications published by the Third Generation Partnership Project (3GPP)

In the radio access system downlink, the adjacent carrier leakage level directly increases as the SFDR decreases, and the traffic capacity of the mobile system deteriorates as a result. In Rel. 8 standardized by the 3GPP, the requirement regarding the adjacent carrier leakage ratio (ACLR) of the transmission signal for the downlink is less than -45 dB.

Fig. 3 shows frequency spectra for the transmitted LTE signal with and without the matching network for both the driver and receiver circuits at the output level of -5 dBm. The figure shows that the driver and receiver circuits with the matching network decreases the adjacent carrier leakage level at the -5 -dBm output level due to the IM3 characteristics generated by the LD or/and PD compared to that without the matching network. The ACLR was measured as a function of the output level, and the minimum ACLRs are -63.5 dB and -64.8 dB with and without the matching networks, respec-

Fig. 3. Measured frequency spectrum of transmission signal at -5 -dBm output level.

tively. Despite the increase in the transmission gain of 14 dB with the matching networks compared to that without the matching networks, a significant increase in the ACLR is not observed.

The RoF link considered in this study satisfies the Rel. 8 specification, and it has the potential to transmit multiple carriers while maintaining the required ACLR. The input and output ranges from -10 dBm to 0 dBm facilitate the design of transmission equipment in terms of level diagrams. Therefore, the driver and receiver circuits with the matching networks exhibit better characteristics in this level range.

The error vector magnitude (EVM) was measured to compare the quality of the data transmission. Fig. 4 shows the I-Q constellations for the driver and receiver circuits with the matching networks. The constellations are for 64QAM and include the total error from all sub-carriers. The points in the constellation at the output level of $+4$ dBm are noisier than those for -5 dBm because the IM3 characteristics increase with the increase in the output level.

The value of the EVM, E_{EVM} , regarding the test transmission signal given in Table I is calculated as

$$E_{\text{EVM}} = \frac{1}{N_{\text{sub_frame}}} \sum_{k=1}^{N_{\text{sub_frame}}} \left\{ \frac{1}{P_{\text{ref}}} \left(\frac{1}{N_{\text{sub_carrier}}} \sum_{n=0}^{N_{\text{sub_carrier}}-1} \sqrt{|e(n)|^2} \right) \right\}, \quad (1)$$

where $N_{\text{sub_frame}}$ represents the number of sub-frames, $N_{\text{sub_carrier}}$ represents the number of sub-carriers, P_{ref} represents the peak reference vector, and e represents the error of the signal, while the EVM for the physical downlink shared channel is analyzed using the vector signal analyzer during 1 frame corresponding to the time period of 10 ms. For the driver and receiver circuits with matching networks, the EVMs are 0.98% and 2.1% at the output levels of -5 dBm and $+4$ dBm, respectively. The EVM was measured as a function of the output level. The measured EVM is less than 1% in the output range of -25 dBm to 0 dBm with the matching networks. Despite the increase in the transmission gain of 14 dB with the matching networks compared to that without the matching networks, no significant increase in the EVM is observed, which is similar to the case with the ACLR.

The adjacent channel selectivity (ACS), which dominates the performance for the radio uplink of the mobile base station, degrades as the SFDR decreases. A SFDR wider than 52 dB satisfies the requirement of the ACS defined in the 3GPP technical standards [4].

Table II gives the achieved characteristics for the proposed RoF link in the 1.5 GHz frequency band. Frequency Division Duplex (FDD) systems are allocated to radio frequency bands from 700 MHz to 2.6 GHz in the 3GPP, and typical occupied bandwidths of LTE systems are from 1.4 to 20 MHz. These results show that the proposed technique is applicable to RoF links for digital mobile systems.

(a) EVM is 0.98% at -5 dBm output level.

(b) EVM is 2.1% at +4 dBm output level.

Fig. 4. Measured I-Q constellation diagram of transmission signal at output of RoF link employing driver and receiver circuits with matching networks.

Table II. Achieved characteristics for RoF link at frequency of 1.5-GHz band

Reflection coefficient (S11) at input	-15 dB
Reflection coefficient (S22) at output	-15 dB
Gain	+4.2 dB
Intercept Point	+20 dBm at output port
Spurious Free Dynamic Range (SFDR)*	58 dB
Adjacent Channel Leakage Ratio (ACLR)	-63.5 dB at -5-dBm output
Error Vector Magnitude (EVM)	0.98%

*Noise level is evaluated at occupied frequency bandwidth of 10 MHz

4 Conclusion

This paper presents a simple configuration for an analogue RoF system that consists of only two sets of stubbed microstrip lines for impedance matching, a pair comprising a laser diode optical source and p-i-n photodiode, and an optical fiber transmission line. This simple configuration exhibits the gain of +4.2-dB with a SFDR of 58 dB without any amplifier at 1.5 GHz. The LTE downlink signal is transmitted to show the applicability of the proposed RoF link construction to the antenna system of a mobile base station. An ACLR of less than -63.5 dB and an EVM of less than 1% are achieved at the output power of -5 dBm and in the output range from -25 dBm to 0 dBm. Despite the increase in the transmission gain of 14 dB with the matching network compared to that without the matching network, no significant increases in the ACPR and EVM are observed. These results satisfy the specifications given in the 3GPP technical standards. The results show that a simply and cost-effectively configured RoF link yielding positive gain is achieved and is applicable to feeder lines in the next generation mobile base stations.