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LETTER

Beam control method for analog RoF systems based on pre-beamforming with a few antenna elements

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Abstract Radio over fiber (RoF) is attracting much attention as one way to realize high frequency bands (above about 10 GHz) systems. A fixed wavelength allocation beamforming scheme has been proposed to attain the desired link budget in such systems. However, this beamforming performance is degraded with massive antenna elements, because of increasing the phase error due to chromatic dispersion. Therefore, we propose a novel beam control method for the scheme, that implements beamforming initially with just a few antenna elements negligible beamforming deterioration. In this letter, the proposed method characteristics is evaluated, and the effects of suppressing beamforming deterioration and improving beamforming gain are shown.

Keywords: radio over fiber, high frequency bands, beamforming
Classification: Wireless communication technologies

1. Introduction

Large capacity wireless communication systems using high frequency bands above about 10 GHz are very attractive. However, one problem is the coverage reduction created by propagation loss. Radio over fiber (RoF) technology is one promising solution. RoF technology allows the functions of the conventional wireless base station to be apportioned among central station (CS) with signal processing function and remote radio unit (RRU) with antenna function; multiple simple RRUs are connected to one CS via RoF links [1, 2]. Therefore, the coverage of high frequency bands systems employing RoF technology can be expanded effectively. The RRU is further simplified by using analog RoF than digital RoF, because this makes analog-digital and digital-analog converters unnecessary.

High frequency bands systems require beamforming to attain the desired link budget. To keep each RRU extremely simple and fully utilize the effectiveness of RoF systems, it is desirable to allocate as many functions as possible to the CS. Thus, remote beamforming by the CS is required to perform beamforming in RRUs without signal processing function. Remote beamforming methods have been reported that use the time delays caused by chromatic dispersion [3, 4, 5]. These conventional methods control the beam direction by switching wavelengths. However, these methods have some problems. The conventional methods need to narrow wavelength interval as radio frequency becomes higher or the optical fiber length becomes longer. Therefore, beam control is difficult in high frequency bands RoF system, because closer wavelength interval may be required than spacing between optical carrier and sidebands. In the conventional methods, since massive wavelengths are used for beam control of one RRU, the same wavelength may be used at multiple RRUs connected to same CS. This limit the number of RRUs connected to one CS. Additionally, the conventional methods are necessary to control for switching wavelengths in each RRU. It incurs function addition for RRU. To solve these problems, a remote beamforming scheme with fixed wavelength allocation was proposed [6].

The remote beamforming scheme in [6] allocates fixed wavelengths with narrow spacing and equal intervals. If wavelength bandwidth used beam control is enough narrow, a phase error due to difference of chromatic dispersion is negligible. Thus, a phase difference between adjacent antenna elements created by time delay are assumed equivalent in RRU, and beamforming can be performed. In addition, phase differences of adjacent antenna elements are changed by adding arbitrary phase difference (additional phase interval) beforehand to the signals on each antenna element in CS. Thus, beam direction at RRU is changed. Therefore, remote beam control by CS is possible. However, a phase error due to chromatic dispersion increases with expanding wavelength bandwidth used beam control, and causes beamforming deterioration. It may limit number of antenna elements at RRU. In this letter, a beam control method for the fixed wavelength allocation beamforming scheme is proposed for beamforming with massive antenna elements. The proposed beam control method can suppress beamforming deterioration and achieve beamforming gain.

2. Proposed beam control method

The fixed wavelength allocation beamforming scheme gives phase difference $\Delta\beta$, which occurs by difference of transmission speed of adjoin wavelength, to signals of all antenna elements. $\Delta\beta$ is considered equal under applicable conditions of the fixed wavelength allocation beamforming scheme. However, when antenna elements are increased, beamforming accuracy degrades due to the phase error φ_i created by chromatic dispersion. The proposed beam control method reduces an influence of the phase error and keeps beamforming accuracy. It carries out in two steps: first step is fixed wavelength allocation beamforming with only

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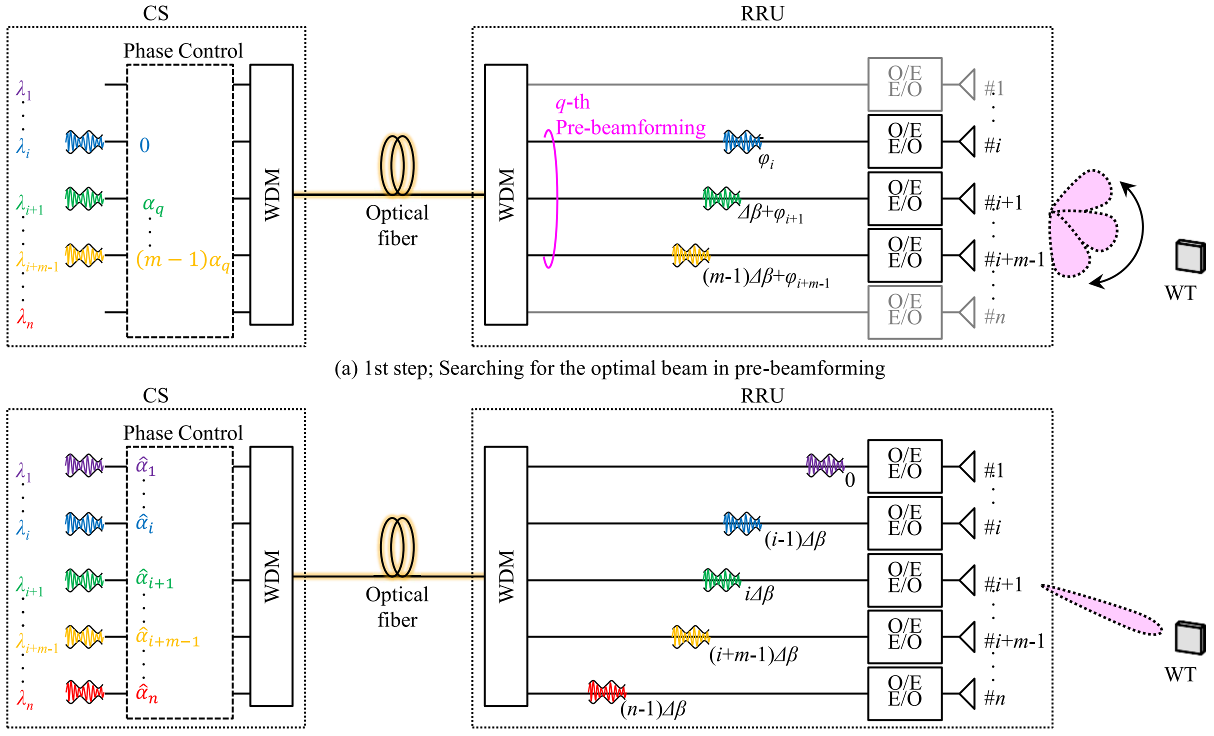

(a) 1st step; Searching for the optimal beam in pre-beamforming

(b) 2nd step; Beamforming with all antenna elements based on pre-beamforming results

Fig. 1 The structure of proposed beam control method

a few antenna elements, second step is fixed wavelength allocation beamforming with all antenna elements based on phase information obtained by 1st step. The 1st step is called "pre-beamforming". Pre-beamforming is performed on all antenna elements while changing the combinations of antenna elements. Furthermore, the adjustment phase of beamforming with all antenna elements is calculated based on the pre-beamforming results. The phase differences between adjacent antenna elements at RRU become almost equal by applying the adjustment phase derived from pre-beamforming in CS. Therefore, beamforming deterioration can be suppressed.

Figures 1(a) and (b) show pre-beamforming (1st step) and all antenna elements beamforming (2nd step), respectively. In 1st step, performing pre-beamforming and calculating optimum adjustment phases for all antenna elements. i ($i = 1, 2, \cdots, n$) is antenna element index, n is number of all antenna elements hosted by RRU. The number of antenna element combinations and antenna elements used in the q-th pre-beamforming ($q = 1, 2, \cdots, p$) are determined by Eq. (1), (2). p represents the number of antenna element combinations carried out pre-beamforming.

$$p = \left\lceil \frac{n-1}{m-1} \right\rceil \tag{1}$$

$$i = j + (q-1)(m-1) \tag{2}$$

where, $\lceil\ .\ \rceil$ is ceiling function, m ($m \geq 2$) is number of antenna elements used in pre-beamforming. j ($j = 1, 2, \cdots, m$) is antenna element index used in pre-beamforming. Note that, in order to obtain the relative phase from the reference antenna element, antenna elements used pre-beamforming must be grouped one or more elements overlap between adjacent groups. In addition, pre-beamforming is always performed with m antenna elements. The optimum additional phase interval α_q in q-th pre-beamforming is determined by performing beam scanning while changing the phase interval at CS, which is based on fixed wavelength allocation beamforming with m antenna elements, and obtaining feedback from wireless terminal (WT). The adjustment phase of the i-th antenna element in beamforming with all antenna elements (2nd step), $\hat{\alpha}_i$, is determined from the optimum additional phase interval α_q which is obtained by q-th pre-beamforming by Eq. (3).

$$\hat{\alpha}_i = (j-1)\alpha_q + \sum_{k}^{q-1}(m-1)\alpha_k \tag{3}$$

In 2nd step, beamforming with all antenna elements is carried out applying the optimum adjustment phases obtained in the 1st step.

Because $\hat{\alpha}_i$ includes a phase which cancels the phase error due to chromatic dispersion, beam misshaping can be suppressed. Therefore, the proposed pre-beamforming method better suppresses beamforming deterioration and improves beamforming characteristics than the existing fixed wavelength allocation beamforming scheme, even if the phase error due to chromatic dispersion is large due to more antenna elements.

3. Evaluating characteristics

In the proposed pre-beamforming method, the beam is swept while changing the phase interval in CS during pre-beamforming. The beam direction is changed continuously according to the phase interval value. The beam can be formed in a more appropriate direction by reducing the search step size of the phase interval. This improves

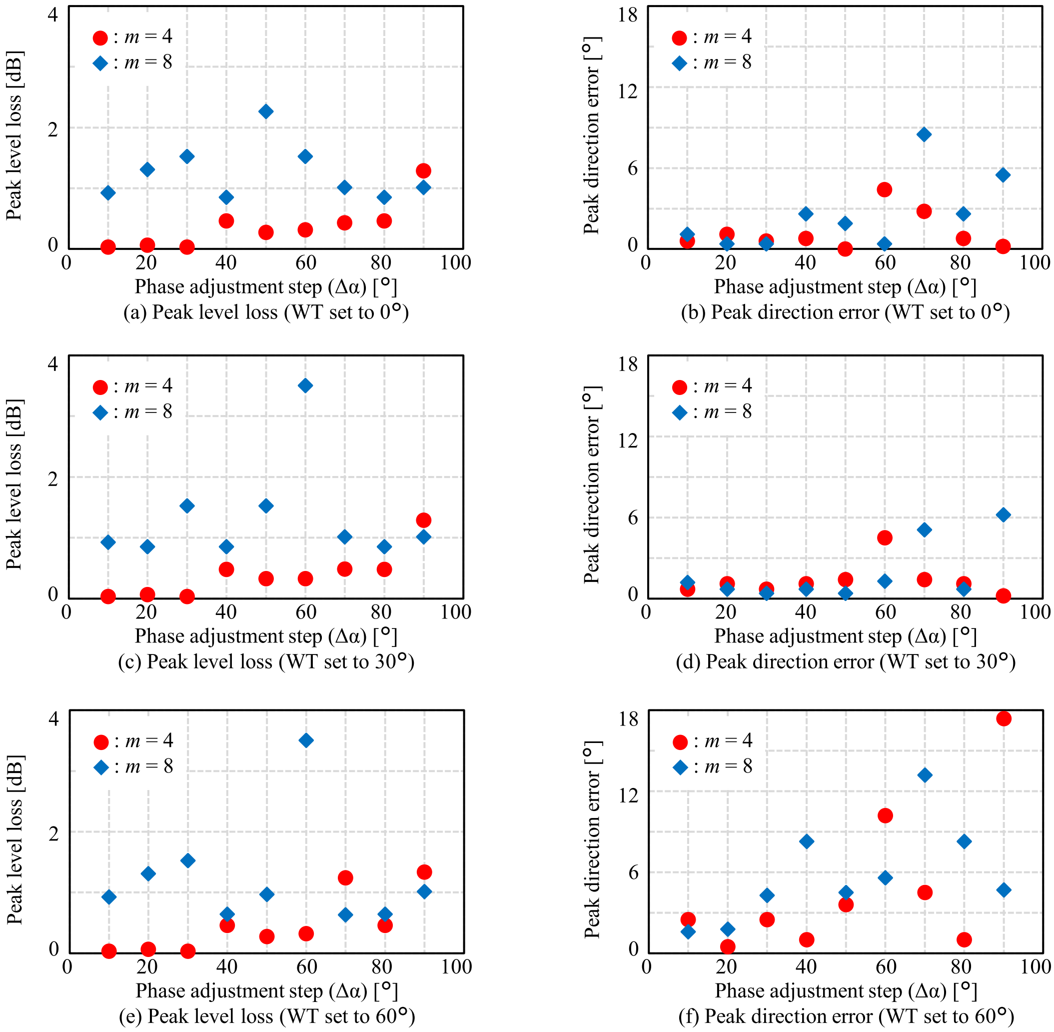

Fig. 2 Simulation results

Table I Simulation parameters

RF	28 GHz
Array antenna in RRU	16 elements linear array Half wavelength spacing
Number of antenna elements used pre-beamforming (m)	4, 8
Phase adjustment step size ($\Delta\alpha$)	10° — 90°
Wavelength / interval	1500 nm band / 100 GHz grid
Optical fiber	20 km SMF
WT position	0°, 30°, 60°

the beamforming characteristics. However, decreasing the phase adjustment step size increases the overhead imposed by pre-beamforming. To investigate this tradeoff, the effect of the phase adjustment step on beamforming performance is simulated.

Simulation parameters are shown in Table I. The number of antenna elements used in pre-beamforming (m) was either 4 or 8. It is confirmed from preliminary simulations that peak level deterioration is negligible, about 1 dB, with m = 4 and 8. Half power beam width (HPBW) and beamforming gain of pre-beamforming with m = 4 and 8 are about 25.2° and 12.4°, about 6.0 dB and 8.3 dB, respectively. The phase adjustment step size ($\Delta\alpha$) was set to $10°, 20°, \cdots, 90°$. WT is set to 0°, 30° and 60° from the front of RRU antenna elements, which means that desired horizontally beam direction was 0°, 30° or 60°. Optical fiber assumed was standard single mode fiber (SMF) specified by ITU-T [7].

Figure 2 shows the simulation results. Figures 2(a), (c) and (e) show peak level loss of proposed beamforming. These values are peak level difference between proposed beam control method and ideal 16 elements linear array beamforming. Figures 2(b), (d) and (f) show that beam direction error of the proposed beamforming relative to the desired beam direction. Red symbols and blue symbols represent the simulation results for the cases of m = 4 and 8, respectively. It is confirmed that the peak level loss and the peak direction error tend to decrease as the phase adjustment step size is decreased until eventually saturating, while they increase as the phase adjustment step size coarsens, regardless of WT position (beam direction). However, when the phase adjustment step size is 40° or more, the beamforming characteristics may deteriorate significantly irrespective of the phase adjustment step size. For example, the peak level loss is about 0.3 dB, while the peak direction error is about 4.4° when m = 4, $\Delta\alpha$ = 60° and WT set to 0° as shown in Figs. 2(a) and (b). Thus, the loss of beamforming gain in desired direction is more than 6.2 dB. The pre-beam direction depends on the phase adjustment step size ($\Delta\alpha$), RF, optical fiber length, used wavelength and interval, and the number of antenna elements used in pre-beamforming (m).

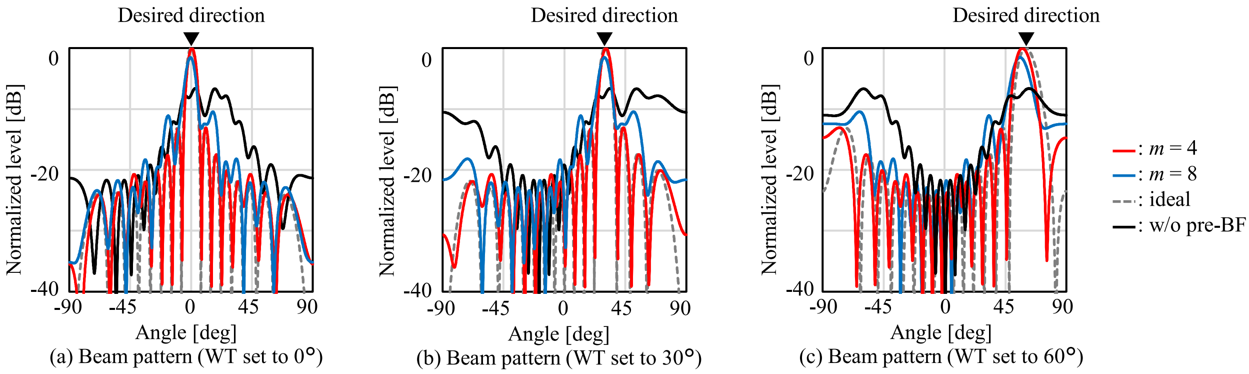

Fig. 3 Beam pattern ($\Delta\alpha$ = 30°)

The pre-beam may not be formed in the desired direction due to combining these parameters in case of $\Delta\alpha > 30°$. Then, adequate α_q cannot be obtained, and significant peak direction error and beamforming gain loss in desired direction are occurred. It is considered that significant peak direction error is occurred unfortunately due to simulation parameters and conditions in this simulation.

Comparing the differences in the number of antenna elements used in pre-beamforming, the peak level loss is smaller when $m = 4$ as shown in Fig. 2(a), (c) and (e). Especially in the case of $\Delta\alpha \leq 30°$, the peak level loss can be negligible when $m = 4$. On the other hand, the peak level loss of about 1 dB occurs when $m = 8$. This is because the beamforming gain degrades by about 1 dB is included already in the optimum additional phase interval α_q in pre-beamforming when $m = 8$. WT is set to 0° or 30°, the peak direction error is less than 1.5° regardless of the number of antenna elements used in pre-beamforming when $\Delta\alpha \leq 30°$ as shown in Figs. 2(b), (d). Since HPBW of ideal 16 elements linear array beamforming is about 6.5° or 7.4° when beam direction is 0° or 30°, the peak direction error less than 1.5° will cause less than 2 dB beamforming gain loss in desired direction. In case of WT set to 60° and $\Delta\alpha = 30°$, the peak direction error is about 2.5° and 4.3° with $m = 4$ and 8. Since HPBW expands as the desired beam direction angle increase, ideal 16 elements linear array beamwidth is about 11.8° when WT is set to 60°. Thus, an influence of the peak direction error becomes relatively small. Then, the beamforming gain loss in desired direction is about 0.5 dB and 2.8 dB with $m = 4$ and 8.

Figure 3 shows beam pattern in case of $\Delta\alpha = 30°$. Red lines and blue lines are results applied pre-beamforming method with $m = 4$ and 8. For comparison, results of ideal 16 elements linear array beamforming and the fixed wavelength allocation beamforming scheme (w/o pre-BF) are shown. These results show that the beamforming gain loss in desired direction (WT set direction) is about 6.8 dB–7.7 dB without pre-beamforming. On the other hand, the results suggest that the pre-beamforming scheme achieves that the beamforming gain loss in desired direction is less than about 0.5 dB and about 3 dB when $m = 4$ and 8, respectively in case of $\Delta\alpha$ is 30° or less. Therefore, it can be confirmed that the peak level loss and the beam direction error by the phase error due to chromatic dispersion can be reduced effectively by applying the proposed method with phase adjustment step size of 30° or less. These results show that the proposed pre-beamforming method can suppress beamforming degradation and improve the beamforming gain.

4. Conclusion

A beam control method for the fixed wavelength allocation beamforming scheme is proposed. This method determines the adjustment phase for all antenna elements beamforming from pre-beamforming results. Pre-beamforming is carried out using only a few antenna elements and maintains beamforming performance. In this letter, the effect of phase adjustment step size on beamforming performance is evaluated. Simulation results show that the proposed pre-beamforming method can suppress beamforming degradation and improve the beamforming gain. When the phase adjustment step size is 30° or less, the beamforming gain deterioration from the ideal beam with 16 elements linear array is less than about 0.5 dB and about 3 dB for the cases of $m = 4$ and 8, respectively. This means that the proposed pre-beamforming method improves beamforming gain by 3 dB or more.

References

[1] J. Beas, G. Castanon, I. Aldaya, A. Aragon-Zavala, and G. Campuzano, "Millimeter-wave frequency radio over fiber systems: a survey," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1593–1619, March 2013. DOI: 10.1109/SURV.2013.013013.00135

[2] V.A. Thomas, M. El-Hajjar, and L. Hanzo, "Performance improvement and cost reduction techniques for radio over fiber communications," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 627–670, Second Quarter 2015. DOI: 10.1109/COMST.2015.2394911

[3] R. Soref, "Optical dispersion technique for time-delay beam steering," *OSA Applied Optics*, vol. 31, no. 35, pp. 7395–7397, 1992. DOI: 10.1364/AO.31.007395

[4] S. Akiba, M. Oishi, Y. Nishikawa, K. Minoguchi, J. Hirokawa, and M. Ando, "Photonic architecture for beam forming of RF phased array antenna," OFC 2014, pp. 1–3, 2014. DOI: 10.1364/OFC.2014.W2A.51

[5] H. Huang, C. Zhang, C. Chen, T. Wu, H. Huang, and K. Qiu, "Optical true time delay pools based centralized beamforming control for wireless base stations phased-array antennas," *J. Lightw. Technol.*, vol. 36, no. 17, pp. 3693–3699, Sept. 2018. DOI: 10.1109/JLT.2018.2849001

[6] K. Ito, M. Suga, Y. Shirato, N. Kita, and T. Onizawa, "Remote beamforming scheme with fixed wavelength allocation for radio-over-fiber systems employing single-mode fiber," *J. Lightw. Technol.*, vol. 40, no. 4, pp. 997–1006, Feb. 2022. DOI: 10.1109/JLT.2021.3127529

[7] ITU-T Rec. G.652, "Characteristics of a single-mode optical fiber and cable," Nov. 2016.