Fiber Length Estimation Method for Beamforming at millimeter Wave Band RoF-FWA System

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Abstract:

To supplant partial optical access networks, we study a large capacity transmission system with millimeter wave applied radio over fiber (RoF). In this system, it is desirable from the viewpoints of downsizing and power saving that the base station (BS) is simplified and the central station (CS) controls beamforming. However, this demands fiber length estimation because each wavelength must be given a different phase rotation due to chromatic dispersion in the optical fiber. This paper proposes a method to estimate fiber length from CS to BS supporting wireless terminal (WT) by utilizing time synchronization; its performance is evaluated.

\textbf{Keywords:} RoF, Millimeter wave, Beamforming

\textbf{Classification:} Wireless communication technologies

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Fig. 1 The structure of proposed method in millimeter wave band RoF-FWA system

1 Introduction
Applying a large capacity communication system that uses millimeter wave links as an alternative to partial optical networks is drawn attention [1]. Existing millimeter wave fixed wireless access (FWA) systems suffer low efficiency because the high propagation loss constrains the communication area. Our solution is a novel FWA system that uses the radio over fiber (RoF) technique; we call it millimeter wave band RoF-FWA system. This system sets the signal processing function and the RF processing function in the central station (CS) and base station (BS), respectively. Larger communication coverage is realized by setting multiple BSs that are connected to one CS via a passive optical network (PON). This provides significant installation advantages as each BS is expected downsizing and power saving by simplifying.

Since millimeter wave band RoF-FWA system utilizes millimeter waves, beamforming is essential. In order to perform beamforming while simplifying all BSs, this system executes beam control in CS [2-3]. When CS controls a beam, a different wavelength is allocated to each antenna element to secure the phases appropriate. However, each wavelength experiences a different phase rotation due to chromatic dispersion in the optical fiber, and this deviation must be cancelled for appropriate beamforming. Since the phase rotation is determined by wavelength and fiber length, fiber length estimation is necessary.

Two fiber length estimation methods are common: using transmission time obtained by optical time domain reflectometer (OTDR) [4] or point to multipoint (P2MP) discovery [5]. Reference [4] estimates the fiber length from the time taken for a pulse signal transmitted by CS is reflecting back by BS. However, multiple BSs connect to one CS as this system, making difficult to apply this method because discerning which BS the signal is reflected from becomes impossible. Reference [5] estimates the fiber length by using P2MP discovery to measure the round trip time (RTT). This method is not suitable for millimeter wave band RoF-FWA system as each BS is made more complicated by the addition of a function that transmits a frame with embedded identifier to CS. Furthermore, even if the fiber length of each BS is obtained by these methods, it is unclear which BS should support the wireless terminal (WT). Therefore existing methods are not suitable
for this system.

We propose a novel fiber length estimation method that utilizes the communication time difference created by two wavelengths obtained by time synchronization. This method can estimate the fiber length from CS to the BS that is supporting the target WT. Since the fiber length estimates include the error imposed by the time synchronization error, this paper clarifies the wavelength setting that minifies the estimation error. In addition, beamforming characteristics achieved with estimated fiber length are evaluated, and the influence of the time synchronization error on beamforming performance is verified by simulations.

2 Proposed fiber length estimation method

The structure of proposed method in millimeter wave band RoF-FWA system shown in Fig. 1. It assumes the use of broad beams that are used to establish a low speed mode for transmitting control signals. CS and WT are time synchronized, downlink and link used different wavelengths. First, CS transmits a training signal from one BS antenna element; WT receives the signal using one WT antenna element. At this point, CS and WT obtain transmission start timing $t_{d,ts}$ and reception start timing $t_{d,rx}$, respectively. Next, WT returns training signal and CS receives this signal using the same antenna elements used for downlink communication. At this point WT and CS obtain transmission start timing $t_{u,ts}$ and reception start timing $t_{u,rx}$, respectively. WT embeds $t_{d,rx}$ and $t_{u,rx}$ in the returning signal, and CS estimates the fiber length from this information. CS obtains downlink and uplink total communication duration, $t_d$ and $t_u$, from transmission and reception start times.

$$t_d = t_{d,rx} - t_{d,tx}$$
$$t_u = t_{u,rx} - t_{u,tx}$$

(1)

Total communication durations can also be given by Eq. (2),

$$t_d = t_{fd} + t_r + t_p$$
$$t_u = t_{fu} + t_r + t_p$$

(2)

where, $t_{fd}$ and $t_{fu}$ are fiber transmission time in downlink and uplink, $t_r$ is wireless transmission time, $t_p$ is total signal processing time at CS, BS, and WT. When calculates the difference between $t_d$ and $t_u$, $t_r$ and $t_p$ cancel out and the difference of $t_{fd}$ and $t_{fu}$ remains as shown in Eq. (3).

$$t_d - t_u = t_{fd} - t_{fu}$$

(3)

In here, fiber transmission time can be obtained by fiber length $l$ and group delay time per distance in downlink and uplink, $\tau_d$, $\tau_u$. It is a known parameter determined by the wavelength used for fiber transmission and the chromatic dispersion of the fiber.

$$t_{fd} = l \cdot \tau_d$$
$$t_{fu} = l \cdot \tau_u$$

(4)

Plugging Eq. (4) into Eq. (3) yields:

$$t_d - t_u = l \cdot \tau_d - l \cdot \tau_u.$$  

(5)

Solving Eq. (5) for $l$ yields:

$$l = \frac{t_d - t_u}{\tau_d - \tau_u}$$

(6)
As shown above, the fiber length can be estimated from measured values and known parameters.

3 Performance evaluations

Actual total communication durations $t_i$ and $t_u$ include measurement error due to the time synchronization error. Therefore, this section confirms which wavelength setting minify the fiber length estimation error and verifies the influence of the time synchronization error on beamforming performance.

3.1 Beamforming scheme

The beamforming scheme used this evaluation directly connects a unique wavelength to each BS antenna element. The phase for beamforming and the added phase rotation created by the chromatic dispersion of $i$-th ($1 \leq i \leq n$) antenna element are represented by $\theta_i$, $\varphi_i$, respectively; $n$ is the number of antenna elements. The phase for beamforming and the added phase rotation are given by Eq. (7), (8)

$$\theta_i = \frac{2\pi d_i \sin \psi}{\lambda_{RF}}$$

$$\varphi_i = 2\pi \cdot f_{RF} \cdot l \cdot \tau_i,$$

where $d_i$ is distance from reference antenna element, $\psi$ is signal arrival direction, $\lambda_{RF}$ is RF wavelength, $f_{RF}$ is RF frequency, $\tau_i$ is the group delay time of $\lambda_i$ (wavelength assigned to $i$-th antenna element). The phase of $i$-th antenna element set in the phase control unit ($\theta_{ICS}$) is shown in Eq. (9).

$$\theta_{ICS} = \theta_i - \varphi_i.$$  

The phase of signal arriving at BS ($\theta_{BS}$) is added $\varphi_i$ in fiber as shown in Eq. (10).

$$\theta_{BS} = \theta_{ICS} + \varphi_i.$$  

Thus, $\varphi_i$ is canceled by fiber transmission and only $\theta_i$ remains, in fact $\theta_{BS} = \theta_i$.

3.2 Simulation

Simulation parameters are shown in Table I. RF frequency is 60 GHz band which is a typical millimeter wave band, and fiber length is 10 km (standard length in optical access networks). The fiber is single mode fiber (SMF), wavelength used fiber length estimation ($\lambda_d$, $\lambda_u$) is 1300 - 1625 nm, these values conform to recommendation ITU-T [6]. Wavelength of fiber transmission is 1300 nm band which is one of common wavelength band used in optical network systems. The allocated wavelengths have equal spacing ($\Delta\lambda$) of 0.2 - 1 nm. Time synchronization error (described below as time error) is 0.1 - 20 ns, it takes account of the accuracy of the global positioning system (GPS).

Fig. 2(a) shows the fiber length estimation error for the wavelengths used, for the case that time error is 1 ns. The four lines show the impact of wavelength difference on fiber length estimation ($|\lambda_d - \lambda_u|$). Since the wavelengths are limited to 1300 - 1625 nm, the plots become shorter as the wavelength difference increases. This figure shows that the fiber length estimation error tends to shrink as the wavelength difference increases. This result is reasonable because large differences in wavelengths yield large differences in fiber transmission time, making the time error relatively small. In addition, since the chromatic dispersion
Increase yields large differences in fiber transmission time, the estimation accuracy improves with longer wavelengths for the same reason. The following evaluation uses wavelengths of 1300 nm and 1500 nm to replicate the wavelengths used in actual optical networks.

Fig. 2(b) shows the beam direction error, which is the deviation from the desired direction of beam, and the time error. The five lines plots the results gained when \( \Delta \lambda \) allocated to eight antenna elements is varied in the range of 0.2-1 nm. It can be confirmed that beam direction accuracy deteriorates in proportion to time error regardless of \( \Delta \lambda \). This is because the fiber length estimation error becomes large as time error increases. It is confirmed that the beam direction error is lower and the beam direction is accurate with \( \Delta \lambda \) is narrower. Since the phase rotation offset is determined by the estimated fiber length in this beamforming scheme (explained in 3.1), the added phase rotation includes error due to fiber estimation error. This error increases with the group delay time as shown in Eq. (8). Therefore, if \( \Delta \lambda \) becomes large and a longer wavelength is used, the error in phase rotation offset increases and beam direction accuracy is degraded. In this evaluation case, even a slight time error yields significant beam direction error that exceeds the half power beam width (HPBW) at \( \Delta \lambda = 1 \) nm. On the other hand, even if the time error is 20 ns, the beam direction error is less than HPBW at \( \Delta \lambda = 0.4 \) nm or less. 0.4 nm is about 70 GHz when converted into a frequency in the optical wavelength band; this spacing is practical if the 60GHz band is used for RF communication.

Fig. 2(c) shows the beam pattern when \( \Delta \lambda \) is 0.4 or 1 nm. In the case of \( \Delta \lambda = 1 \) nm, beam form becomes distorted and the peak level decreases as the time error increases. When the time error is 20 ns, the beamforming gain in the desired direction is reduced by about 12.7 dB compared to that without time error. However, in the case of \( \Delta \lambda = 0.4 \) nm, since the beam direction error is less than HPBW, the beamforming gain decrease in the desired direction is very low, about 1.5 dB, and beam form distortion around the main beam is negligible. The above results show that proposed method is an available way of achieving adequate beamforming gain in the desired direction with low degradation using practical parameter.

4 Conclusion

We proposed a fiber length estimation method based on time synchronization for a millimeter wave band RoF-FWA system. This paper examined the wavelength setting to reduce the fiber length estimation error and evaluated the influence of time error on beamforming accuracy. Simulations showed that the fiber length estimation error tends to fall as the wavelength difference widens or longer wavelengths are used. The results showed that proposed method makes beamforming possible with high accuracy as the beam direction error can be reduced to under the HPBW and the beamforming gain degradation on the desired direction is about 1.5 dB or so in the case of practical wavelength intervals.
**Table I.** Simulation parameters

| Parameter                                      | Value                        |
|------------------------------------------------|------------------------------|
| RF frequency                                   | 60 GHz band                  |
| BS antenna                                     | 8 antenna element linear array |
| Half wavelength spacing                        |                              |
| Fiber type                                     | SMF [6]                      |
| Fiber length                                   | 10 km                        |
| Wavelength used fiber length estimation \( (\lambda_d, \lambda_u) \) | 1300 – 1625 nm               |
| Wavelength of fiber transmission \( (\lambda_i) \) | 1300 nm band                |
| Wavelength spacing \( (\Delta \lambda) \)      | 0.2 - 1 nm                   |
| Time error                                     | 0.1 - 20 ns                  |

![Simulation results](image)

*Fig. 2* Simulation results