Optical True Time Delay Pools based Centralized Beamforming Control for Wireless Base Stations Phased-Array Antennas

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***Abstract*—In this paper, we propose a novel centralized beamforming control system, using optical true time delay pools (OTTD-Ps), for multiple base stations (BSs) of wireless communication with phased array antennas (PAAs). In this proposed system, the pre-designed OTTD-P with an interconnection matrix (ICM) and a wavelength-controlling matrix (WCM) is employed to control microwave beam steering (MBS) and the controlling function is carried out in a central station (CS). Dense wavelength division multiplexing based de-multiplexer (DMUX) is used to replace tunable filters in BS and the cost-effective multi-wavelength laser source (MLS) is employed to generate uniformly spaced optical carriers in the CS. Without tunable filters and controlling modules, as well as the controlling function of beamforming in different BSs being concentrated in the CS, the complexity and cost of BSs can be greatly reduced. Finally, a proof-of-concept system employing OTTD-P with 24 wavelengths and 4-element antennas, which are able to form 7 basic PAA beams, is demonstrated. The obtained results successfully verify the feasibility of the proposed scheme.**

***Index Terms*—Centralized beamforming control system, optical true time delay pool, microwave beam steering.**

I. INTRODUCTION

IN wireless communication, it never stops excavating the pursuit of higher speed and larger capacity. For example, the future 5G wireless networks are expected to provide 1000 times higher wireless capacity compared with the 4G wireless networks [1]. The radio-over-fiber (RoF) systems can be employed at different radio-frequency (RF) bands, because the transparent transport of analog or digital signals and the dynamic spectrum allocation in wireless communication are also available. In particular, the structure of RoF networks greatly reduces the complexity of base stations (BSs), since the functions of RF carrier generation, modulation and multiplexing are carried out at a central station (CS) [2]. In [3], we have demonstrated a distributed stabilized- phase antenna system for the RoF links, where all optical carriers were generated by an optical frequency comb.

The wireless communication capacity can be dramatically increased by employing the spatial division multiplexing technology [4]. Nowadays, phased-antenna array (PAA) has been extensively used to realize microwave beamforming because of its steering capability and compactness. In wireless communication deployments, the BS with PAA can achieve extreme sharp beams with a high spatial resolution and a beamforming gain, which can provide the flexible spatial multiplexing capability, improve the received power and suppress multi-user interference [5], [6]. In addition, beam steering is required to guarantee wireless connections due to inevitable user mobility in wireless communication scenarios [7]. In [8], a multiple simultaneous beam generation scheme has been proposed based on acousto-optic PAAs beamformer. After that, the use of optical multiple beamforming for wireless base stations with PAAs has been proposed, in which how optical technology was inserted into these communication antenna systems [9]. Compared with the electrical phase shifters, the method of optical true time delay (OTTD) has larger bandwidth, higher compactness and lower loss [10], [11]. Moreover, the PAA system based on RF is easy to be integrated with the RoF networks without increasing the overall cost [7]. However, as the communication traffic demands increase dramatically, the future wireless communication architecture consists of ultra-dense small cells [12] and the microwave beamforming mode in the BSs inevitably leads to high cost.

In the past few years, the optical beamforming for PAAs has been widely studied. In [13], an OTTD system based on free space optics has been proposed, where the microwave signal was modulated onto an optical carrier and then passed along different optical paths to realize diverse OTTD values.

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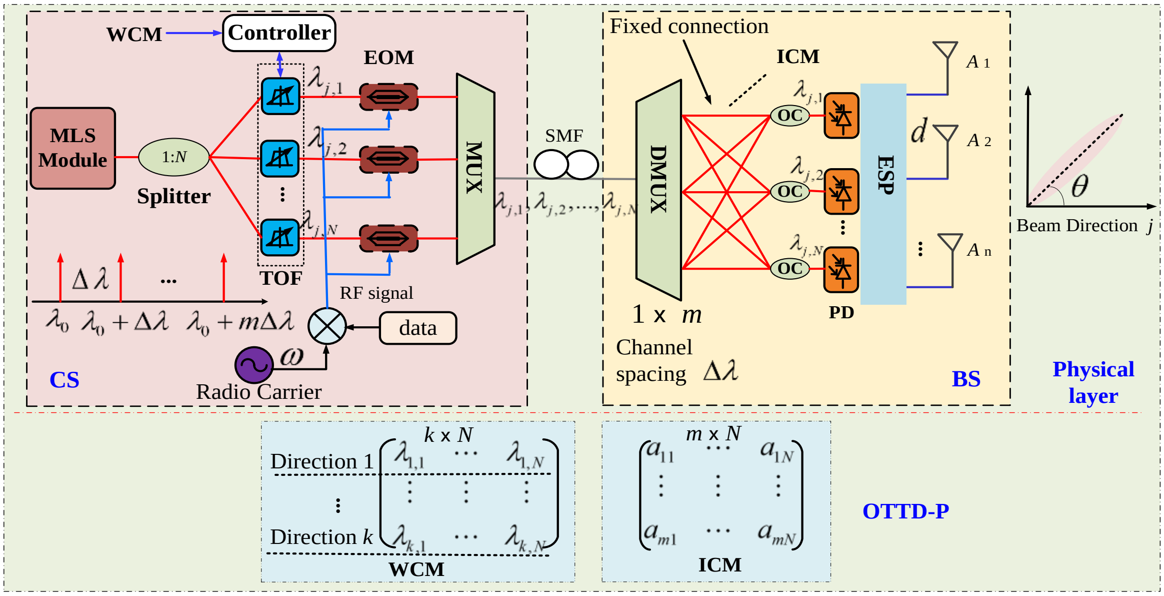

Fig. 1. Structure of centralized beamforming control system by using OTTD-P for PAAs. TOF: tunable optical filters, EOM: electro-optical modulator, MUX: multiplexer, SMF: single mode fiber, DMUX: de-multiplexer, OC: optical coupler; PD: photodetector, ESP: electronic signal processing.

Another important approach to obtain the OTTD was achieved by using dispersion materials such as dispersion compensating fibers, fiber gratings [14]-[16]. It is interesting to note that a very simple dispersive method has been proposed [17], in which all of the fibers have the same length. What's more, tunable laser source or tunable laser array can also be applied to obtain the optical beamforming for PAAs [18], [19]. Some technologies such as wavelength division multiplexing can be introduced into photonic beamformer to reduce cost and complexity [6], [20], [21].

In this paper, we propose a novel centralized beamforming control system by using OTTD pools (OTTD-Ps) for low-cost wireless communications. The OTDD-P includes an interconnection matrix (ICM) and a wavelength-controlling matrix (WCM), and is used for controlling beam steering. All complex functions of microwave beamforming in multiple BSs are concentrated in one CS. Moreover, dense wavelength division multiplexing based de-multiplexers (DMUXs) are used in BSs to replace tunable filters and the well-designed multi-wavelength laser source (MLS) is employed to generate uniformly-spaced optical carriers in the CS. The MLS generates optical carriers, the WCM controls the beamforming directions, and the ICM describes the specific connection between different channels and antennas in multiple BSs. By using the pre-designed OTTD-P, any beamforming in the multiple BSs can be available in the centralized controlling manner.

II. PRINCIPLES

A. OTTD-P with Centralized Controlling Modules

The structure of centralized beamforming control system by using OTTD-P for PAAs in wireless BSs is depicted in Fig. 1, which consists of both the physical layer and the OTTD-P. The physical layer contains main physical devices used for implementing the centralized beamforming control in both CS and BS except operational amplifier and the electronic signal processing (ESP) devices after photodetectors (PDs). The pre-designed matrixes of ICM and WCM are just employed to describe the proposed system and we call them OTTD-P, in which WCM and ICM are used to describe the control of beamforming, and describe the special connection between channels of DMUX and PDs, respectively. Here, we just takes the structure with one BS as an example to show the principle of our method. The structure with multiple BSs is an extension with multiple parallel structures of single BS. All controlling operations of multi-BSs are implemented in one CS by the RoF links, and the connection in BSs is fixed by using passive devices DMUX, which can simplify the structure and reduce the difficulty of BSs upgrading.

Firstly, the uniformly-spaced optical frequency comb lines are generated by MLS in the CS, and it is assumed that the spacing between these adjacent comb lines is $\Delta\lambda$ which matches the channel spacing of DMUX used in the BS. Moreover, the number of all needed comb lines is set to m. The output is divided into N parts by a passive splitter before filtering. The tunable optical filters (TOFs) are then used to select N comb lines as optical carriers for the N-element antenna array as shown in Fig. 2. For different N comb lines, different time delay values are introduced for PAAs and the corresponding beam direction can be obtained in the BS. Assumed that the number of beamforming direction needed in the BS is k. For direction j, a specific set of wavelengths $\lambda_{j,1},\lambda_{j,2},\ldots,\lambda_{j,N}$ can meet it. The specific wavelength set is determined by the principle of one-dimension N-element PAAs. So wavelength sets for all beamforming directions can be described as a $k \times N$ matrix named WCM. Namely, each row in the WCM expresses one beamforming direction. The "Controller" module in Fig. 1 is a physical device used for controlling TOF to pick out the needed N comb lines. For example, if the TOF is an optical filter tuned by temperature, the "Controller" module is temperature controller of TOF.

When beamforming direction *j* is needed in the BS, the temperature controller is used for tuning TOF to pick out the corresponding *N* optical comb lines in the CS due to the *j*-th row of WCM.

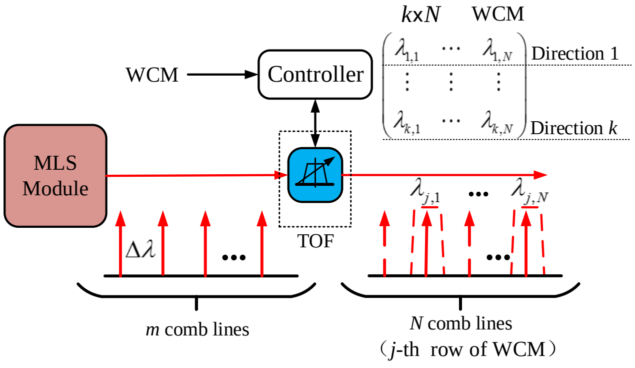

Fig. 2. Principle of WCM in a CS.

Secondly, the RF signals are modulated on those selected *N* comb lines. They are coupled into the single mode fiber (SMF) after a dense wavelength division multiplexer and then transferred to the BS. The time delay difference $\Delta\tau$ between antenna *i* and antenna *j* can be expressed as,

$$\Delta\tau_{i,j} = (j-i)\Delta\lambda DL, \tag{1}$$

where $\Delta\lambda$ is the wavelength spacing between these adjacent comb lines, $1 \le i < j \le N$, D and L are the dispersion coefficient and the length of SMF.

Thirdly, a passive device DMUX is employed rather than TOFs in the BS to minimize the cost and complexity of the BS. Namely, the connections between channels of DMUX and antennas are fixed. For example, as mentioned above, a specific set of wavelengths $\lambda_{j,1}, \lambda_{j,2}, ..., \lambda_{j,N}$ is used to form direction *j* which is consisted of *N* specific comb lines. So the matched *N* channels of DMUX in the BS are sequentially connected the *N* PDs through optical couplers (OCs). Noted that *m* comb lines and *m* channels of DMUX are matched. But *m* is bigger than *N*, the OCs are used to connect *m* channels and *N* PDs as shown in Fig. 1. Similarly, for the other direction, the connection corresponding to it is also obtained. After PDs, the detected RF signals have been introduced specific time delay. And the corresponding beamforming can be generated after the ESP such as electrical filtering.

To better describe the connections, $m \times N$ ICM is defined and shown in Fig. 3. However, in Fig.3, to better explain the specific connection we omit some physical devices. To minimize the cost and complexity, the BSs do not have tunable functions and just with some passive devices. So the connections in the BS are limited, that is, each channel of DMUX is not connected with different antennas. The ICM is determine by the WCM so the limitation should be considered in the design of WCM. The deployment scenarios of beamforming mainly include macro coverage, high-rise coverage, heterogeneous network, indoor, and outdoor hotspots. Thus, the beamforming positions in the future wireless communication are some stationary scenes. So it can be confirmed in advance. Based on OTTD-P, all needed beamforming can be obtained and the controlling process is centralized in the CS.

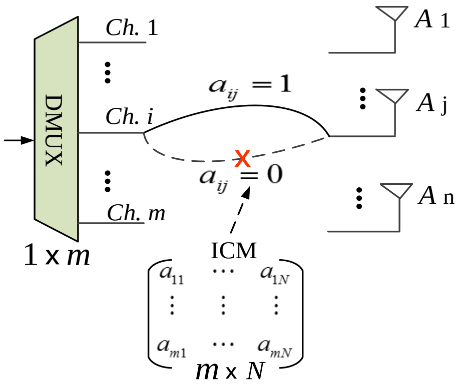

Fig. 3. Principle of ICM in a BS. *Ch. i*: channel *i*.

B. Optical Loss in Centralized Beamforming Control System

The proposed centralized beamforming control system can be deemed to a RoF system as shown in Fig. 4 and its optical loss is discussed next.

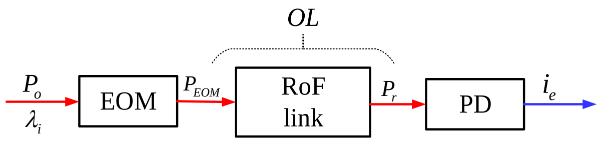

Fig. 4. Optical loss of the centralized beamforming control system. OL: optical loss.

The Mach-Zehnder modulator and avalanche diode are employed in this work, and assumed that the power of comb line λ_i is P_o. The output power P_{EOM} of modulator is then approximately expressed as,

$$P_{EOM} = \frac{P_o}{2}[1 - J_0(\pi\frac{V_{RF}}{V_\pi})\cos(\pi\frac{V_{bias}}{V_\pi})], \tag{2}$$

where V_{RF} is the peak voltage of RF signal, V_{bias} and V_π are the bias voltage and the half-wave voltage of Mach-Zehnder modulator, and J_0 is the first Bessel function of zero order.

The optical loss *OL* in RoF links includes the loss of fiber link, the insertion loss l_{in} of devices, and the splice loss l_{sp}, it can be represented as,

$$OL = \sum l_{in} + \sum l_{sp} + \alpha L, \tag{3}$$

in which α and L are the attenuation coefficient and the length of SMF. So the optical power detected by PD is,

$$P_r = P_{EOM} 10^{\frac{OL}{10}}. \tag{4}$$

Finally, the detection current $i_e = M\Re P_r$ can be obtained, in which M and $\Re$ are the gain and the responsivity of PD.

We implement our centralized beamforming control system in C band with 1550 nm center wavelength. So the above-mentioned optical loss of beamforming system can be compensated by an erbium-doped fiber amplifier (EDFA). The gain of EDFA is expressed as,

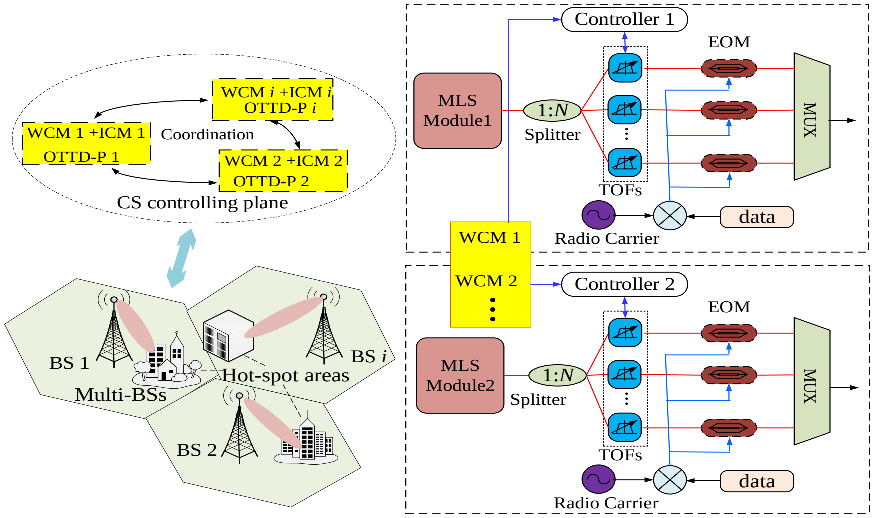

Fig. 5. Structure of multiple BSs cooperation beamforming with the centralized control beamforming by using OTTD-Ps.

$$G = \frac{G_0}{1 + (G_0 \frac{P}{P_{\max}})}, \tag{5}$$

where G_0 is the small-signal gain of EDFA and $P_{\max}$ is the maximum power of working EDFA.

C. Cooperation Beamforming and Centralized Control for Multiple BSs

A potential application of our centralized beamforming control system is an alternative plan for ultra-dense network in the future wireless communication systems, as shown in Fig. 5. The controlling functions of cooperation beamforming for multiple BSs are reconstructed by multiple OTTD-Ps, and can be deployed centrally in the CS. In this architecture, the inter-cell inference between l BSs can be suppressed by the cooperation beamforming of multiple BSs, since the controlling functions for different BSs are centralized on the CS controlling plane, which can make a reasonable use of resource by on-demand allocation.

The use of optical multiple beamforming for wireless BSs has been introduced one efficient way of frequency reuse by spatial multiplexing based on the PAAs [9]. The phased array is used to prevent within cell mobile to mobile crosstalk, and reduce BS to BS interference, in which all the BSs would be connected via the dedicated links typically. However, as shown in Fig. 5, all beamforming control modules in this proposed system for multiple BSs are centralized in one CS. So the BSs in our optical beamforming system do not need to be connected by the dedicated links. The "links" between BSs can be completed by the OTTD-Ps at the level of software in the CS, which is named by the CS controlling plane. The physical implementation for multiple BSs is described in the right part of Fig. 5, in which the BSs are ignored to highlight the centralized control for multiple BSs in the CS. Obviously, the structure with multiple BSs is an extension with the multiple parallel structures of the system with one BS.

In Fig. 5, the optical beamforming matrix for multiple BSs based PAAs is written as,

$$\begin{bmatrix} e^{-j\varphi_{1,1}} & e^{-j\varphi_{2,1}} & \cdots & e^{-j\varphi_{N,1}} \\ \vdots & \vdots & & \vdots \\ e^{-j\varphi_{1,l}} & e^{-j\varphi_{2,l}} & \cdots & e^{-j\varphi_{N,l}} \end{bmatrix}, \tag{6}$$

where the number of BSs is l and $\varphi_{t,i}$ is the phase difference between the t-th antenna element and the reference antenna element. Assumed that the location of hot spots needed beamforming for the r-th BS is $L_r(\rho, \theta)$, where ρ and θ are the pole axis and the polar angle. Due to locations $L_r(\rho, \theta)$, the optical beamforming matrix can be determined, as shown in Fig. 5, and the beams are pointed to "Hot-spot" areas.

III. DESIGN EXAMPLE AND RESULTS

A designed system of centralized control beamforming based on OTTD-P for 4-element PAAs is schematically shown in Fig. 6, where the MLS has 24 output optical comb lines with the central wavelength of 1550 nm and the wavelength spacing $\Delta\lambda$ =100 GHz.

The OTTD-P units for 4-element PAAs and 7-direction are then designed, in which 7 rows of WCM possess approximately incremental wavelength intervals written as $\Delta\lambda$, 2 $\Delta\lambda$, … , and 7 $\Delta\lambda$. The element of WCM $\lambda_{i,j}$ shown in Fig. 6 means that the i-th comb line of MLS is used for carrying RF signals to the j-th antenna through SMF. According to the WCM, the corresponding ICM can be obtained.

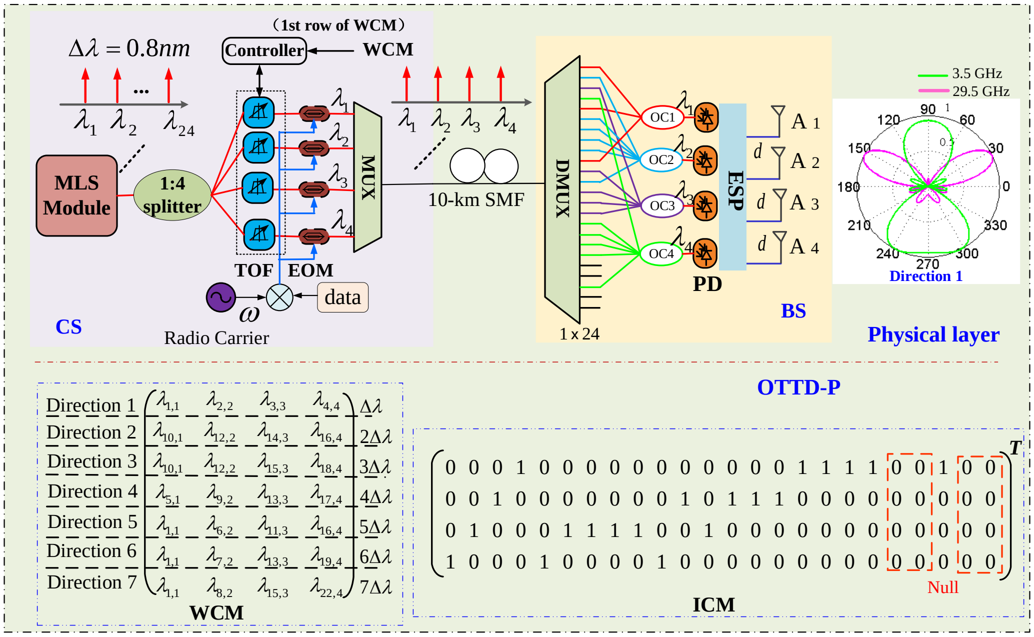

Fig. 6. Example of 4-element centralized beamforming control system based OTTD-P with 24 output optical combs, OTTD-P consisted of 7x4 WCM and 24x4 ICM for 7 beamforming directions.

As stated above, the WCM is designed to meet with the limitation that the same comb line cannot be employed in different columns of WCM. It is assumed that the optical comb line λ_i of MLS is both the elements $\lambda_{j,k}$ and $\lambda_{r,t}$ of WCM. For direction *j* or *r*, we choose the *j*-th or the *r*-th rows in WCM and use TOF to pick out the corresponding optical comb lines, which both consist of the comb line λ_i. Due to the definition of $\lambda_{j,k}$ and $\lambda_{r,t}$, the comb line λ_i can not be separated by DMUX in the BS. The OTTD-P consists of a 7×4 WCM and a 24×4 ICM. We can get any needed beam-pointing by designing an appropriate OTTD-P.

Take the beamforming direction 1 as an example, firstly, the 1st row of WCM $\lambda_{1,1},\lambda_{2,2},\lambda_{3,3},\lambda_{4,4}$ is used. And the TOFs filter the comb lines generated by the MLS, the specific comb lines $\lambda_1,\lambda_2,\lambda_3,\lambda_4$ are obtained. Secondly, the optical signals are coupled into optical fiber after modulation. By 10-km SMF, the time delay was obtained, as shown in Fig. 7 (a). The connection between DMUX and PD is fixed and shown in Fig. 6. The ICM is used to describe the connection better. For example, the first row of ICM “1000” represents that the 1st channel of DMUX is connected with the antenna 1. Similarly, the 2nd row “0100” represents that the 2nd channel is connected with antenna 2. Finally, after detection and electrical signal processing, the PAAs beam pattern results of direction 1 are got. In our system, the designed 7 directions of beamforming are just used to verify the feasibility of the proposed centralized control system based on OTTD-P. Therefore, in the future wireless communication, our method can be applied in the typical scenarios of high capacity and hot spots such as dense residential areas, dense urban areas, campus, open-air gathering, stadium, subway, and apartment, by designing the MBF system according to the obtained OTTD-P.

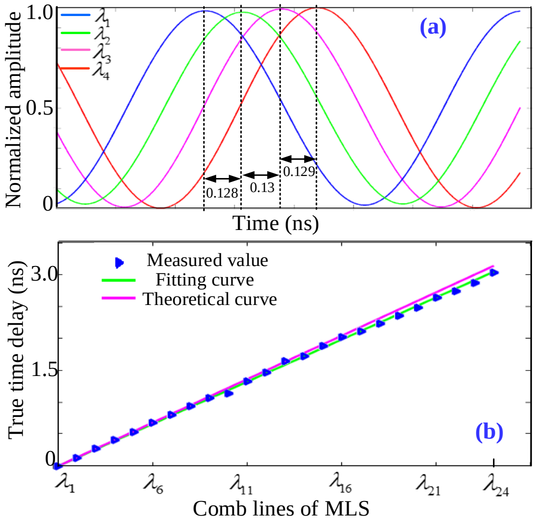

Fig. 7. (a) OTTD introduced by comb lines $\lambda_1,\lambda_2,\lambda_3,\lambda_4$, (b) Measured, theoretical and fitting results of OTTD for all optical comb lines.

The four optical comb lines $\lambda_1,\lambda_2,\lambda_3,\lambda_4$ are modulated by the RF signals and transmitted through a 10 km SMF. The OTTD between the RF signals introduced by four adjacent optical comb lines is shown in Fig. 7(a). Furthermore, to measure the time delay values of all comb lines generated by the MLS, we fix one laser wavelength at λ_1 and tune another laser wavelengths from λ_1 to λ_{24}, in which the wavelength difference between λ_1 and λ_i is $(i-1)\Delta\lambda$. Then the RF signals are modulated on them. After transmission of 10-km SMF, the obtained results are described in Fig. 7(b). According to $\Delta\tau=\Delta\lambda DL$, we can find that the theoretical values of OTTD for 0.8 nm wavelength difference (100 GHz frequency spacing in C band) through 10 km SMF is 0.136

ns. By fitting the measured results, we can obtain that the time delay values for 0.8 nm wavelength spacing is 0.132 ns.

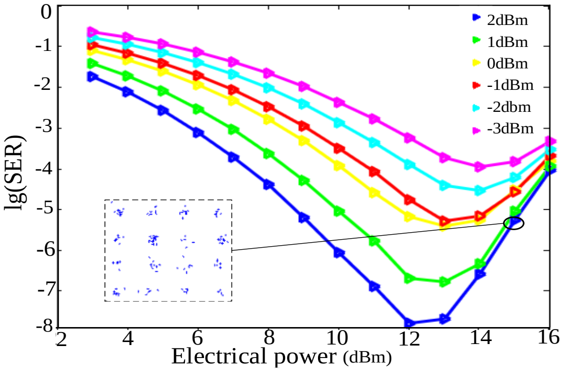

Fig. 8. SER vs. electrical power in optical beamforming control system for 16 QAM with different optical carrier powers.

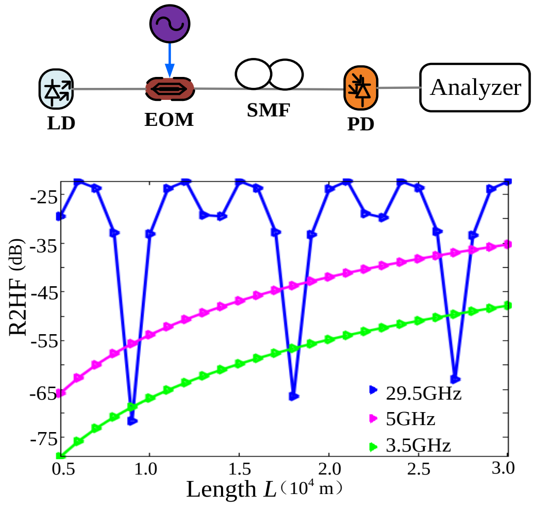

Fig. 9. The R2HF deteriorates with fiber length for 3.5 GHz, 5 GHz, and 29.5 GHz frequencies.

Fig. 8 shows the relationship between the symbol error rate (SER) and the electrical power for 32 Mb/s data using 16 QAM with different optical carrier powers. Firstly, we fix the power of optical carrier as -3 dBm, in which the optical carrier modulated by the electrical signals transfers through a 10-km SMF. By tuning the electrical powers from 3 dBm to 16 dBm and repeating the aforementioned steps, we then have obtained the SER as shown in Fig. 8 with the purple curve. With increasing optical power from -3 dBm to 2 dBm, the results of SER can be obtained similarly. It is found that the noise is dominant at the low electrical power region in the RoF system. With the increase of the electrical power, the SER is reduced. However, the nonlinear distortions such as the 3rd order inter-modulation increase at the high electrical power regain, which greatly deteriorates the system performance.

From Eq. (1), the value of time delay $\Delta\lambda DL$ can be enlarged by increasing the length of SMF L, which is 0.132 ns with 10-km SMF. However, the RF signals are affected by the optical fiber links. Firstly, a sinusoidal signal with 3.5 GHz frequency is modulated on optical carries and transmit it in fibers with different lengths from 5 km to 30 km, as shown in the upper of Fig. 9. And the ratio of the 2nd harmonic and the fundamental (R2HF) deteriorates with the increasing of fiber length. Similarly, the results of R2HF for 5 GHz and 29.5 GHz are obtained. It is interesting to note that the periodic change of R2HF for 29.5 GHz which is shown in the lower of Fig. 9. Due to the employed double-sideband modulation, the RF power after PD is proportional to $\cos^2(4\pi^2\beta_2 f_{RF}^2 L/2)$ which is the periodic function. Therefore, the length of fiber L affects the beamforming precision and the system performance of the proposed optical beamforming system based on OTTD-P.

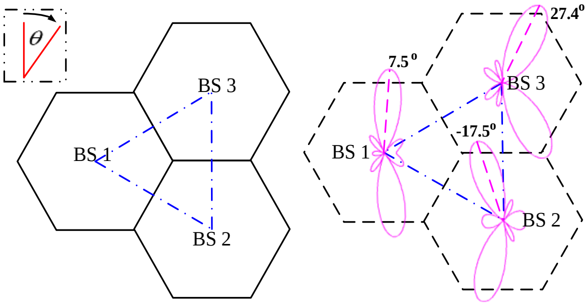

Fig. 10. Multiple beamforming for 3-BSs with 4-element PAAs.

Based on the proposed centralized beamforming control system, the results of multiple beamforming for 3 BSs are shown in Fig. 10. The left part describes the typical cellular mobile communication system in which the wireless signal is radiated to all directions of the covered region. And the right part shows the results of this system with the beamforming for 3-BSs with PAAs. The strategy of interference suppression is multi-cell cooperation based on the centralized controlling module. As discussed above, we got the results of multiple beamforming, in which we assumed that the distribution of 3 BSs is a triangular of the equated triangle and the angles of the cooperation beamforming in 3 BSs are 7.5°, -17.5° and 27.4°, respectively. And the corresponding implementations include designing of OTTD-Ps for 3 BSs and forming of beams.

IV. CONCLUSIONS

A centralized beamforming control system based on OTTD-P has been proposed, which can enable multi-BS cooperative beamforming for the wireless communication. In this scheme, all complex functions of beam steering for BSs have been concentrated in the CS. The pre-designed OTDD-P is determined by the MLS, WCM and ICM, and used to perform the controlling function of beamforming. A proof-of-concept system with 4-element antenna and 7 basic beamforming directions has been demonstrated. For 3.5 GHz and 29.5 GHz frequencies, we have shown that a designed OTTD-P with 0.132 ns time delay unit can offer the steering of 7 beamforming directions. The proposed centralized control system offers flexible beamforming choices by using

OTTD-P and physical layer decoupling. Moreover, the inter-cell inference between multiple BSs was suppressed by the way of multiple BSs cooperative beamforming controlled in the CS controlling plane. The results for 3-BS cooperative beamforming with the angles of 7.5 °, -17.5 °, and 27.4 ° have verified the suppression of inter-cell inference.

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