Large Scale optical controlled mm-wave beam steering system for non-terrestrial network

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Abstract

Non-terrestrial networks' primary benefits their ability to give worldwide coverage, completing and enhancing terrestrial networks in the air, sea, forest, and distant locations. Optical wireless communication is progressively taking the place of non-terrestrial inner network connectivity. Beamforming is necessary to concentrate the energy and lower power usage. The optical control mm-wave beam-steering system in this situation not only fixes the broadband beam squint issue, but also works well with optical wireless communication. Because of arrayed waveguide grating routers (AWGR), we suggest and verified a sizable optical controlled mm-wave phased array beam-steering system.

Introduction

Satellites are attractive to both developed and developing countries because of their wide coverage. Low earth orbit(LEO) satellite networks enable ubiquitous wireless coverage, which facilitates information access in non-urban areas of terrestrial networks. LEO satellites serve a wide range of audiences, including aircraft, ships, and automobiles, which in turn places a demand on beam flexibility. Beamforming is an essential technology in user-customized design. In the 3GPP next generation communication protocol [1], satellite Internet is defined as a complement to terrestrial Internet.

First, in 1995 Frigyes et al. used optical techniques to solve various approaches to the fundamental problem of broadband phased arrays, namely the most critical beam strabismus [2]. Xu et al. 1996 demonstrated a real-time delay-line phased array antenna feeding system based on a multi-channel optical outlier detection technique [3]. Corral et al. in 1997 proposed and demonstrated a new approach for real-time delay (TTD) optical feeding of phased array antennas [4]. Yegnanarayanan et al. proposed and demonstrated the extension to a two-dimensional (2-D) antenna array with independent control of azimuth and elevation angles by using an intermediate-stage optical wavelength conversion [5]. Lee et al. proposed an optical real-time delayed beamforming system using dispersion-compensating fiber and multi-wavelength lasers for phased-array antennas in 2011 [6]. However, the efficiency of the photovoltaic conversion and the high complexity of the system prevent the extensive use of delay lines to compensate for each antenna array in large scale arrays. And in satellite communications, a wide range of scans is necessary, especially for low orbiting satellites. We therefore propose a two-stage optical controlled phased array antenna. For large angle scans, the optical true-time-delay is used to compensate for the large delay difference. And simultaneously compatible with multi-band communication to overcome the phased array aperture effect.

In section 2, the idea of using an optically controlled phased array-based subarray was proposes and theoretically demonstrates its enhancement of the bandwidth performance of broadband phased arrays. The feasibility of the optical controlled millimeter wave phased array structure based on the arrayed waveguide grating routers(AWGR) structure is experimentally demonstrated in section 3. Section 4 provides a summary and outlook.

Optical controlled phased array

The structure of the large-scale optical-assisted phased array is shown in Figure 1. The whole structure has two stages, the first stage uses optical true-time delay(OTTD) to compensate for the true-time-delay of a wide range of scans; the second stage uses a digital phase shifter to achieve high precision scans. In this uniform linear array, the total number of array elements is $N = M \times m$. The antenna array is divided into M sub-arrays, which use an OTTD as delay compensation. Each subarray has m internal array elements and uses a digital phase shifter to shift the phase.

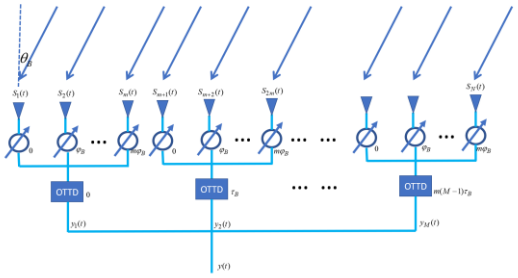


Figure1. Optical controlled phased array architecture

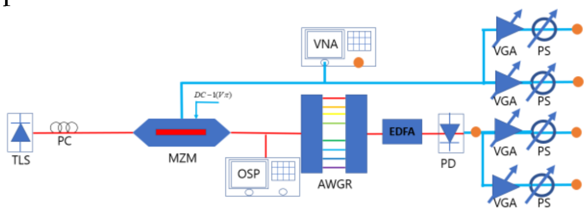


Figure 2 Schematic diagram of the measurement setup. TLS: tunable laser source; MZM: Mach–Zehnder modulator; PC: polarization controller; OSP: Optical Spectroscope; VNA: vector network analyzer; EDFA: Erbium-doped fiber amplifier; AWGR: arrayed waveguide gratings router; PD: photodiode; VGA: Variable gain amplifier; PS: Phase shifter.

The time difference between two adjacent array elements $\tau = d\sin\theta / c$, where d is the distance between two antenna array elements, c is the light speed, θ represents the beam angle. As the phase difference is $\varphi = 2\pi d\sin\theta / \lambda_0$,where λ_0 is the center frequency of the signal. For example, when beam pointing at θ_B , the time-delay and phase difference can be expressed as $\tau_B = d\sin\theta_B / c$ and $\varphi_B = 2\pi d\sin\theta / \lambda_0$, respectively. Assume the first receiver signal is $s(t) = e^{j\varphi(t)}$,every subarray phase difference of the digital phase shifter can be expressed as: $\alpha_B = [1, e^{-j\phi_b}, e^{-j2\phi_b}, \cdots\cdots, e^{-j(m-1)\phi_b}]^T$ .And the i^{th} subarray true time delay is: $\alpha_B = [1, e^{-j\phi[N-1-m(i-1)]}, \cdots\cdots, e^{-j\phi(N-mi)}]^T$ .The i^{th} subarray synthesis signal is: $y_i(t) = {\alpha_B}^T \bullet \alpha_s(i) \bullet s(t), \quad i = 1,2,\cdots,M$ The total array synthesis signal is:

$$y(t) = \sum_{i=1}^{M} y_i[t - m(i-1)\tau_B] \ . \qquad (1)$$

For a conventional phased array, the beam squint is easy to occur when performing broadband signal transmission. Deflection angle of the beam $\Delta\theta_f \approx -\tan\theta_B \Delta f / f_0$, where

Δf is the half bandwidth of wide band signal, and f_0 is the center frequency of the wide band signal. As normal, the maximum deflection angle $\Delta\theta_{f\max} \le \Delta\theta_{1/2}/4$, where $\Delta\theta_{1/2}$ is the half power beam width (HPBW), when $\theta_B = 60^o$. Assume $\Delta\theta_{1/2} = 2^\circ$, the $\Delta f_{\max}/f_0$ was limited to 0.02. It narrows the bandwidth of signal. As insert an OTTD, length l, time delay τ_A , the antenna crossing time can easily reduce as $T_A' = T_A - \tau_A = L\sin\theta_B / c - l / c$. The deflection angle could rewrite as

$$\Delta\theta'_f \approx -(\Delta f / f_0)(1 - \tau_A / T_A)\tan\theta_B \ . \qquad (2)$$

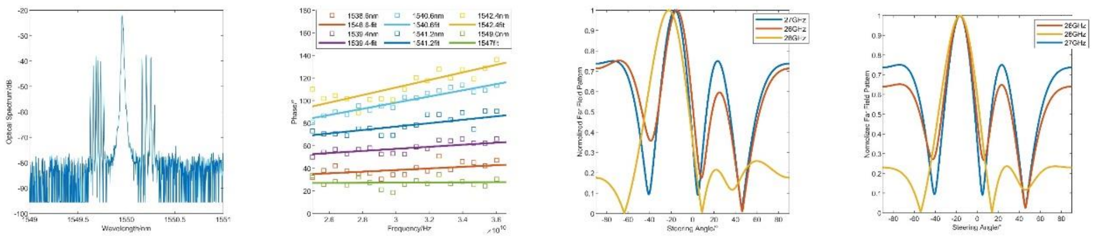
If $T_A = \tau_A$, $\Delta\theta'_f = 0$, there is no antenna across time. Cleverly reducing the complexity of the system by decomposing the subarray, as shown in Fig.1, to reduce the impact of the crossing time on the beam. In this architecture, the OTTD time delay in Mth subarray can be selected as $\tau_M = m(M-1)d\sin\theta_B / c$, which makes the signals of each sub-array located in the θ_B direction of the beam will have no time difference. The phase shift value provided by the i^{th} digital phase shifter within each antenna sub-array is $i\varphi_B$. Although the internal subarray still receives the effect of transition time and aperture effect, each subarray beam will still squint. However, the aperture area of each subarray is reduced to 1/M of the original, so the aperture crossing time will be reduced to T_A / M of the original. Therefore, the system limits on the instantaneous signal bandwidth can be relaxed by a factor of M by allowing a subarray beam offset angle of 1/4 the HPBW, $\Delta f_{max} / f_0 \le M \bullet \Delta\theta_{1/2} / 2\sin\theta_B$.

Experiment and Results

The key components of the experiment are a tunable laser source (TLS Santec MLS-2100) and two symmetrical AWGRs (Gemfire 80ch AWG DMX). TLS control the true-time-delay value via adjusting the wavelength. Tunable optical carriers generated by the TSLs is coupled and fed into an Mach–Zehnder modulator(MZM) via a polarization controller. The optical carrier is modulated by the RF signal generated by the vector network analyzer (VNA, Agilent Technologies PNA Network Analyzer E8361C). The VNA generates millimeter wave RF signals in the frequency range from 25 GHz to 36 GHz. Erbium-doped fiber amplifier(EDFA) is used to compensate for the loss of symmetrical AWGR to ensure that the optical power at the input PD(XPDV2120RA) is 0 dBm, which is in the linear area of photodiode(PD). The Variable gain amplifier(VGA) on the RF board is used to balance the amplitude of the two sub-arrays. The S_{21} phase response of each link is obtained experimentally by detecting the signals fed back from the different output points (e.g., Figure 2, orange monitoring point).

The experimental results are shown in Figure 3. Figure3(a) is the optical domain spectrum after observing the modulation through the spectrometer. By appropriately adjusting V_π , the modulated signal lies in the linear region of the MZM. The phase response obtained at the detection point PD allows to analyze the delay generated by the different wavelengths of optical carriers passing through the AWGR. By fitting the data, we obtain different time delays: 0.058434 micro second, 0.71755 micro second,, 0.91651 micro second, 2.736 micro second, 1.5178 micro second, 3.3476 micro second. Due to the instability of the PD, there are 20 Pico second errors in the delay-time.

In Fig 3(b), the digital phase shifter is given a different amount of phase shift by the beam pointing principle. The beam pointing of -16.56° at 27 GHz is achieved. However, without OTTD, the beam points at -14.76° and -22° at 26 GHz and 28 GHz, respectively. This has a large pointing error. Therefore, the S_{21} phase response of each path was remeasured using the experimental set-up as shown in Fig 2. The S_{21} phase response of each path was remeasured using the experimental equipment as in Figure 2. After re-calculating each phase for beam synthesis, the beam is no longer shifted at 26 GHz, 27 GHz and 28 GHz.



(a) (b) (c) (d)

Figure 3. Experimental results：(a) Spectrograms; (b) Different wavelength delay time; (c) Phase response of AWGR; (d) Optical controlled phased-array far-field pattern

Conclusion

In this paper, the results of the vector network analyzer test verified the compensation of the crossing time by using symmetric AWGR-based OTTD on the subarray. It reduces the beam pointing shift of the phased-array antenna in broadband wide-angle scanning. The advantage of using AWGR in the future lies more in the conversion of WDM to air-division multiplexing in all-optical satellite Internet, and the combination of optical multiplexing mode and RF multiplexing mode is realized to increase the throughput capacity of the satellite under the restricted frequency band. In the next step we will further use AWGR compensation for a wide range of angles and adjust the digital phase shifter for fine angle scanning experiments.

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