Wide FoV Autonomous Beamformer Supporting Multiple Beams and Multi-Band Operation for 5G Mobile Fronthaul

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Abstract: An autonomous beamformer covering 24-37 GHz for fiber-wireless network demonstrates multi-beam and multi-band signal transmission with wide-FoV (110º-180º) self-steering beam-tracking/-forming over a 10-km fiber and 56-cm wireless link for future dynamic 5G-NR fronthaul applications.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2360) Fiber optics links and subsystems

1. Introduction

Next-generation wireless networks require high-capacity access nodes for extremely broadband mobile links over multiple non-contiguous mm-Wave bands. For instance, 5G new radio (NR) systems necessitate remote radio units (RRU) and user equipment (UE) to operate with multiple mm-Wave bands (e.g., at 24/28/37/39/43 GHz) to support multi-standard communication and international roaming (Fig. 1a). Moreover, massive multiple-input multiple-output (MIMO) and phased array architectures are extensively utilized to improve mm-Wave link performance and spatial diversity via beamforming and null-steering interference. Increased number of data streams can be facilitated in future 5G NR, which are highly deployed into frequency and space division to support high-data-rate spectral and spatial signal multiplexing (Fig. 1b). The multi-band 5G MIMO systems residing in RRUs are expected to concurrently handle multiple beams/streams signals [1]. However, unlike conventional static mm-Wave beamforming or satellite communication, many future mm-Wave links are expected to operate in highly "dynamic" latency-sensitive environments, such as AR/VR and vehicle-/drone-based communication, necessitating fast and precise beamforming for multiple signals with distinct Angle-of-Arrival (AoA). Therefore, mm-Wave transceiver (TX/RX) frontends should support high-reliability operations and handle fast-changing multi-beam wideband signal scenarios (Fig. 1c).

To achieve extensively spectral and spatial division in a fiber-wireless system, wideband beamformer can be implemented via photonic-assisted methods, mm-Wave or intermediate frequency (IF) frontends. First, photonic-aid beamformer in the optical link can achieve higher operation bandwidth with array waveguide grating and dispersive fiber [2]; however, its bulky sizes limit the feasibility to use and it is difficult to precisely and stably align the beam toward the incoming signal since the system is sensitive to environmental vibration and temperature variation. On the other hand, extreme multi-band beamforming operations at mm-Wave frontend require extremely broadband power generation and need judicious frequency planning to avoid image jamming [3], which normally lead to a power-hungry and low-efficiency design. While, IF beamforming may be a promising candidate for fiber-wireless network since it can operate with less DC power consumption in a large phased array and it can be easily reconfigured to non-contiguous multi-band 5G NR via different up-/down-conversion local oscillator (LO) frequencies. However, most aforementioned existing mm-Wave fiber-wireless beamforming systems are limited by open-loop operations, which requires extensive phase control signals [4]. Multiple tunings and calibrations are required to achieve precise multiple multi-band signal beam-forming/-tracking, thus it is challenging for future 5G ultra-reliable low-latency networks.

To address these challenges in future dynamic multi-beam and multi-band mm-Wave mobile applications, we present a scalable wide Field-of-View (FoV) autonomous beamformer system for mm-Wave 5G NR fiber-wireless network over 10 km fiber link. The autonomous beamformer achieves calibration-free IF beamforming on multiple multi-band 5G NR signals simultaneously with multiple delay-locked-loop (DLL) phase domain negative feedback

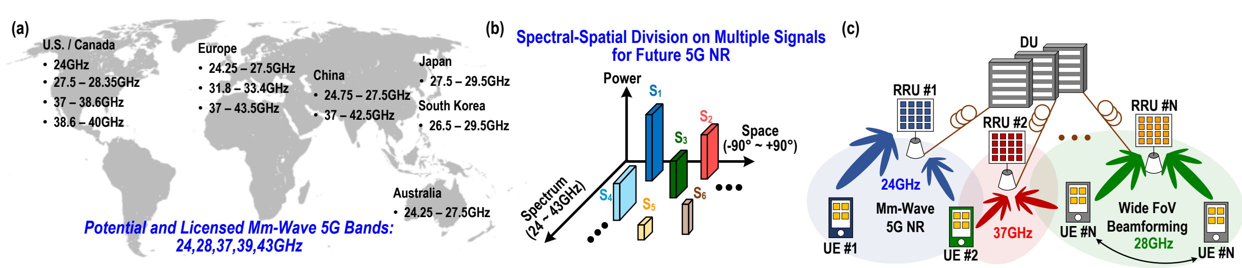

Fig. 1 (a) Global spectrum allocations for mm-Wave 5G NR. (b) Extensive spectral-spatial division for massive multi-signal 5G NR communication. (c) Future dynamic multi-band and spatially multi-beam 5G fiber-wireless communication.

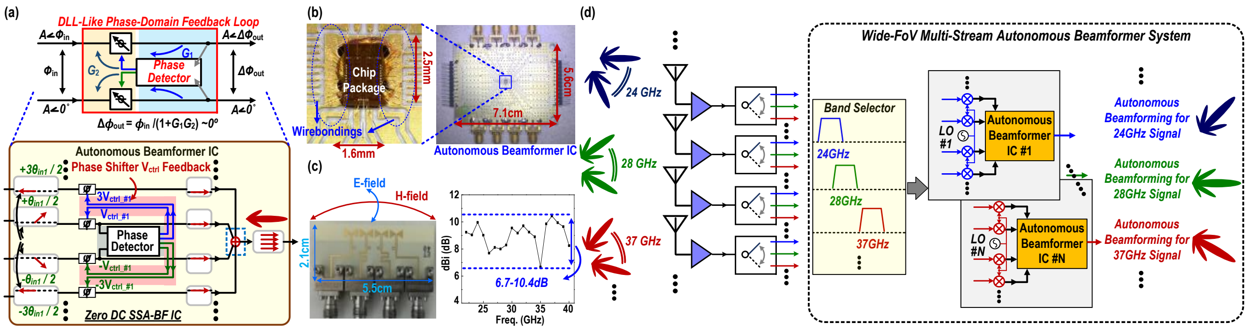

Fig. 2 (a) Operation principle of the full-FoV DLL-based negative feedback. (b)Full package of the beamformer IC. (c) Measured 1×4 antenna array pattern. (d) Proposed autonomous beamformer system for multiple signal beamforming.

loops for supporting multi-wideband signal modulations [5]. Moreover, a mm-Wave antenna array with 22-40GHz bandwidth is designed for the proposed autonomous beamformer receiver array in the 5G fiber-wireless network. Without any prior AoA information, a proof-of-concept mm-Wave fiber-wireless autonomous beamformer system demonstrates that it can accurately align multiple desired signals over wide FoV and multiple 5G NR frequency bands.

2. Operation Principle and Experimental Results

The closed-loop autonomous beamformer array consists of a power-aware phase detector, time-delay-based LC synthetic phase shifters, and progressive feedback control voltage generation as an array-based closed-loop beamformer [5]. In the feedback operation (Fig. 2(a)), the phase detector (phase-to-voltage conversion G_1) first senses phase difference of the adjacent channels and then generates a set of progressive feedback control voltages to a DLL-based voltage-controlled phase shifters (voltage-to-phase conversion G_2) for compensating the phase difference, achieving a total large loop gain = G_1G_2 in the autonomous operation over wide FoV [5]. The beamformer IC package is operated at IF with a compact size with 4mm^2 (Fig. 2(b)) and a 1x4 homemade antenna array is wideband 22-40GHz with a flat antenna gain 6.7-10.4 dBi (Fig. 2(c)). Then, multiple autonomous beamformer with multiple down-conversion LOs are combined for autonomous multi-beam multi-band signals beamforming (Fig. 2(d)).

The experimental setup of the proposed multi-beam and multi-band 5G mobile fronthaul is illustrated in Fig. 3. Due to the equipment restriction in our lab, we apply two 5G NR bands with central frequencies of 24.75 GHz and 37GHz as a proof-of-concept demonstration. To support IF beamforming at RRU side, IF-over-fiber becomes a suitable technique in a balance of spectral efficiency, power amplifier (PA) efficiency, hardware complexity of RRUs and fiber chromatic dispersion. 1Gbaud 4GHz IF signals are generated via a 16GSa/s arbitrary waveform generator (AWG) and then sent into a 10-GHz direct modulation distributed feedback (DFB) laser with central wavelength of 1550.76 nm and 3.5-dBm output optical power. After 10-km mobile fronthauling, a 10-GHz photodetector (PD) is used to convert optical signal to electrical domain. For 24.75GHz 5G NR channel, a mixer and a local oscillator (LO) at 20.75GHz are employed to up-convert the IF signal. After boosting via a 30dB gain PA, the mm-Wave signal is transmitted over 56 cm wireless link. A duplicated link is also implemented for the 37GHz mm-Wave signal, with 33GHz LO instead. A home-designed wideband 1x4 end-fire antenna is employed for receiving the multi-beam multi-band signals. The antenna frequency response and the corresponding spectrum of the received multi-band signal are inset in Fig. 3. Four wideband (24-40GHz) low noise amplifiers (LNA) with 2dB noise figure are employed to compensate the wireless propagation loss of mm-Wave. 2 sets of multi-band selectors are implemented via mm-Wave bandpass filters. The electrical switches and passive mm-Wave bandpass filters are mature devices. They are cost-effective and widely applied in commercial systems for suppressing unwanted out-of-band noise and image jamming. After frequency selection, mm-Wave signals are converted to 5GHz central frequency for IF home-designed autonomous beamformer [5]. After analog-to-digital conversion via a 20GSa/s real time oscilloscope (RTS), the received signals are then evaluated via Keysight Vector Signal Analysis software in terms of their EVM, SNR, and constellation diagrams.

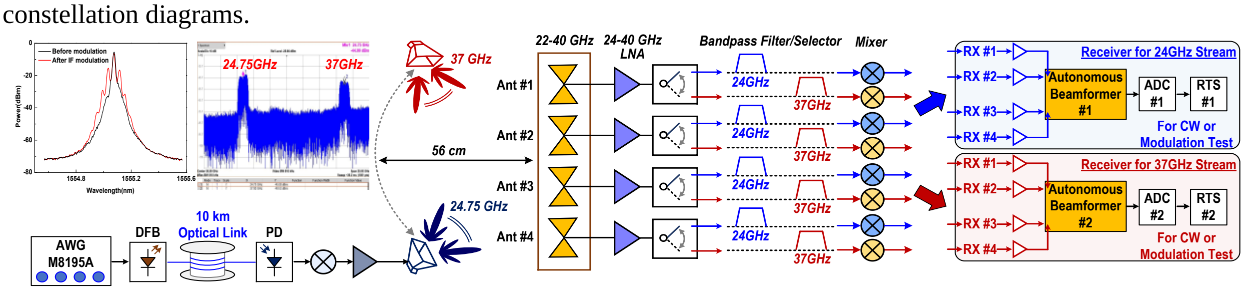

Fig. 3 Measurement setup for the proposed mm-Wave multi-beam and multi-band autonomous fiber-wireless beamformer network.

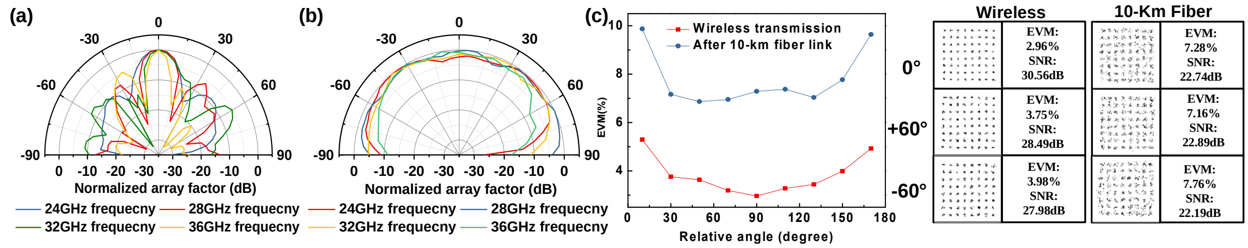

Fig. 4 Normalized antenna array factor versus different incident angles (a) 1x4 end-fire antenna and (b) with the proposed beamformer. (c) The received EVM performance of 64QAM 24.75GHz mm-Wave signal under various relative angles with 37GHz signals coexisting in the RX frontend.

The normalized array factor with and without the home-designed beamformer are displayed in Fig. 4(a) and (b). As one can note that the main peak of array factor is slightly narrower as the mm-Wave frequency increasing. This will increase the difficult of beam alignment for mm-Wave systems. While, the proposed beamformer can track the main beam and steer the received angle toward the input signals. Thus, wide filed-of-view (FoV) multi-beam signals can be supported. The covered FoV, defined as 6dB down of the normalized array factor, of 24-, 28-, 32- and 36-GHz are 155^o, 180^o, 170^o and 110^o, respectively. This can be understood since the 1x4 end-fire antenna is a differential design and optimized for 28GHz. As the mm-Wave frequencies driving away from the 28GHz will cause distortion of the antenna pattern and thus restricted the FoV. We first investigate the relative motion of two special beams with 1Gbaud signals of 24.75GHz and 37GHz. In this case, 37GHz signal is fixed at position of 90^o and 24.75GHz signal is sweeping from 80^o to -80^o, resulting relative angles from 10^o to 170^o. The received EVM performance is central-symmetric as CW testing shown in Fig. 4(b). This implies additional multi-beam signals from different incident angle can be treated individually with neglectable interference. The corresponding constellations are inset in Fig. 4(c).

Fig. 5(a) shows EVM performance versus incident angles of 24.75GHz signal. It performs similar with and without multibeam signal and less than 4% EVM deviation is measured over 80^o FoV. Fig. 5(b) exhibits the bit-error-rate (BER) performance of 24.75GHz 16QAM mm-Wave signal with the proposed beamformer of 0^o and 80^o incident angles after 10-km fronthauling. Again, the received performance is similar even when multi-beam signal is coexisted at the receiver frontend. The received sensitivities, defined as the received power at the FEC criterion, are -4 and -1dBm for 0^o and 80^o incident angles, respectively. Similar evaluation is conducted for 37GHz mm-Wave signal and shown in Fig. 5(c) and (d). Since the power attenuation for wireless propagation loss and cable loss for 24.75GHz and 37GHz are 3.49 dB and 1.37dB. The received SNR for 37GHz signal is thus dropped by 4.86dB, and the corresponding EVM dropped by 6.4% at 0^o incident angle as compared to 24.75GHz signal. The received sensitivities after 10-km fronthauling of 37GHz with 4QAM signal can achieved -3.5 and -2.5dBm for 0^o and 80^o incident angles, respectively.

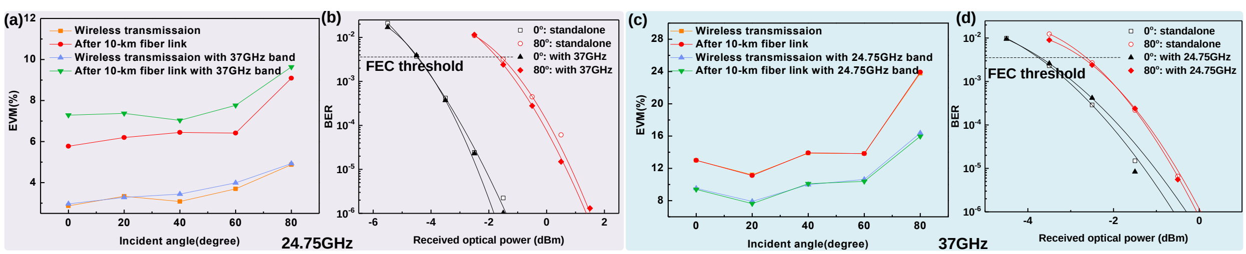

Fig. 5 The received EVM performance of 1Gbaud mm-Wave signal under various incident angles (a) 24.75GHz and (c) 37GHz. BER performance of 0^o and 80^o incident angle of (b) 24.75GHz and (d) 37GHz signal.

4. Conclusion

The proposed autonomous fiber-wireless beamformer system demonstrates self-steering beam-tracking/-forming on multiple wireless multi-band signals. Our experimental results show an autonomous beamformer system covering wide FoV (110^o-180^o) beamforming with a wideband 22-40GHz antenna array as well as simultaneously receiving dual-band (24.75 and 37 GHz) signals with enhanced mobile data-rate multi-Gbps transmission over 0.56-m wireless and 10-km fiber link, enabling future high capacity, multi-beam and multi-band 5G mobile fronthaul applications.

5. References

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