Photonic Delay Processing With Centralized Etalon Cascade for Radio Beamsteering in Simplified 2 × 5 Phased-Array Radio Heads

Aina Val Martí, Graduate Student Member, IEEE, David Löschenbrand, Member, IEEE, Markus Hofer, Member, IEEE, Thomas Zemen, Senior Member, IEEE, and Bernhard Schrenk, Member, IEEE

Abstract—The adoption of beam-centric radio communication schemes calls for efficient methods of beamforming with multi-element antennas. We present a delay generation method that employs a shared and centralized cascade of Gires-Tournois etalons for element-by-element radio frequency beamsteering at remote radio heads, thus adding no complexity at the antenna site. We experimentally demonstrate beamsteering of up to 32° in combination with a 2 × 5 phased-array antenna operated at a radio carrier frequency of 3.5 GHz and transmitting 64-ary quadrature amplitude modulated, orthogonal frequency division modulated radio signals. The radio transmission performance over mobile optical fronthaul and free-space radio propagation is evaluated through offline error vector magnitude estimation and real-time transmission of high-definition video traffic. We further show carrier phase switching at 2 kHz using direct emission frequency modulation of the involved optical light sources, proving the proposed concept to support the fast tracking of mobile users.

Index Terms—5G, microwave photonics, mobile fronthaul, optical communication terminals, RF beamforming.

I. INTRODUCTION

It is well known that the number of users demanding wireless data is hugely increasing. One solution to face the increase in capacity and spectral efficiency needed, is beamforming in combination with multi-element antennas, which allow to improve the capacity and data rates of wireless systems through mitigating interference at the same time. Together with centralized baseband processing, multiple-input / multiple-output (MIMO) schemes and the support for higher carrier frequencies, it is touted as the key enablers for future beam-centric radio access networks [1]. The formation of radio beams in mm-wave massive MIMO configurations can be accomplished by tailoring the complex amplitude of the radio carrier frequency. One way to do so is the adoption of a programmable true-time delay (TTD) associated to each antenna element [2]. While radio frequency (RF) based TTDs are difficult to implement over a wide frequency range, rendering them as a bandwidth-limiting factor, the off-loading of TTD to opto-electronic functions can mitigate this pivotal performance bottleneck: Transparent photonic beamforming methods have been shown to be compatible with wide signal bandwidths and a fast tuning response, which makes them of great interest.

The scientific contribution of this work is a method for photonic-assisted RF beamsteering with a centralized, shared delay generator. We accomplish this task without changing the outside fiber plant of the mobile fronthaul network, nor is beamforming circuitry employed at the distributed antenna sites. We will experimentally demonstrate beamsteering of up to 32° at 3.5 GHz with a phased-array 2 × 5 antenna configuration enabled through wavelength-specific delay tuning with a cascade of Gires-Tournois etalons, which is shared among wavelength sets. We experimentally confirm the quality of analogue radio-over-fiber and free-space RF signal transmission through offline error estimation and real-time data transfer. Furthermore, we demonstrate that the proposed concept can support for fast beamsteering at 2 kHz through direct frequency modulation of optical source lasers.

The paper is organized as follows. Section II relates the present work to the state-of-the-art in photonic beamforming demonstrations. Section III discusses and characterizes the beamforming method based on a shared etalon cascade. Section IV elaborates on the experimental setup used for performance evaluation. Section V elaborates on the beamsteering capability offered from the proposed concept, while Section VI evaluates the RF transmission performance. Section VII extends the evaluation through real-time signal analysis and video transmission. Section VIII investigates possibilities for fast switching of the carrier phase. Finally, Section IX, concludes the work.

II. RF BEAMFORMING ASSISTED BY PHOTONIC PHASE PROCESSORS

With the advent of cloud-based processing for radio access networks, the mobile optical fronthaul has become indispensable for a seamless connectivity between simplified remote radio
heads (RRH) and centralized baseband units (BBU). Fig. 1 presents such an optically hauled radio access network, which can feature either digitized or analogue radio-over-fiber transmission schemes [3]. For the simplified yet challenging method of analogue optical RF signal transmission, the optical layer can adopt additional functions aiming at all-optical signal processing. A representative scenario is the off-loading of carrier phase manipulation to optical TTD circuits in order to enable RF beamforming with multi-element antennas at the RRHs. In case that the optical TTD function can be facilitated in a shared manner, meaning that it is centralized at the central office (CO), the RRHs, which resemble the distributed tail-end units that feed the mobile equipment (ME) of the radio access network, can be further simplified (Fig. 1).

Towards the direction of TTDs, research work has pursued optically-assisted RF beamsteering, with the aim to achieve a wide RF frequency range by virtue of the broadband nature of photonics, while minimizing the TTD loss at the same time. Waveguide-based or optically switched delay lines, such as shown in [4], [5], can be realized on a very small footprint exploiting photonic integrated circuits to create a TTD. Despite the compactness and scalability, it can only provide a discrete setting for the introduced delay. With this, it does not address the continuous delay adjustment requirements of future radio networks, so that highly directional beam characteristics can be used with precise pointing. Towards this direction, Table I summarizes suitable technology concepts adopted in earlier beamforming demonstrations. A straight-forward method is to set a variable optical delay per antenna element feed. In order not to increase the fronthaul fiber count when centralizing the required optical delay generator, multi-core fibers have been proposed to accomplish a per-core delay encoding when feeding the RRH [6], [7]. Continuous delay settings can also be obtained exploiting a shared dispersive media, such as the transmission fiber in [8], [9], specialized fiber [10], [11], or linearly chirped gratings [12]–[17]. In these schemes, a stable optical source is precisely tuned along a wavelength-dependent dispersion slope. As it is demonstrated in [15], [16], beamsteering can be accomplished in two dimensions, defining an elevation and azimuth angle for the radio beam at the same time. More compact elements that offer a tunable group delay have been demonstrated exploiting optical resonances. This method has been shown in combination with silicon micro-ring resonators [18] or silicon waveguide gratings [19]. However, the tuning mechanism can become complex and bandwidth limitations might arise. An option to reduce the complexity in tuning is provided through Gires-Tournois or Fabry-Pérot type etalons [20]–[23]. In this work, we extend our initial findings on shared delay dissemination through a Gires-Tournois etalon [23], by incorporating a second C-band wavelength set that is processed through the centralized etalon for the purpose of real-time radio signal transmission involving a high-definition video feed.

It shall be noted that the tuning speed of optically-assisted beamforming concepts can be fast, with response time in the μs to ns range, as evidenced in [11], [12], [14]–[19]. Moreover, both low sub-6GHz and high RF carrier frequencies in the mm-wave range and beyond are supported [6], [7], [20].

III. SHARED ETALON CASCADE FOR RF BEAMFORMING

In order to accomplish beamsteering, the mobile optical fronthaul shall adopt the notion of analogue radio-over-fiber transmission in combination with optical signal processing. Fig. 2 introduces the fundamental scheme of the beamsteering concept. The radio signal associated to a RRH is jointly modulated on an ensemble of optical carriers, herein referred to as wavelength set. This set is then demultiplexed at the antenna site to feed each antenna element with a different wavelength of this set. In order to introduce an element-specific phase shift for the RF carrier, the wavelength set is tailored in its spectral characteristics by traversing a TTD that ideally allows for a setting on a per-wavelength basis as the entire set passes through the shared delay element. The latter can be realized using an optical all-pass filter structure [24].

A. Gires-Tournois Etalon Cascade

This work employs a cascade of Gires-Tournois etalons [20], [21], [25], [26] for the purpose of optically-assisted RF beamsteering. The etalons of the wavelength-shared cascade are characterized by an optical thickness $d$, a reflectance $R$ at their front facet and a highly reflective back facet. The cascade of $N$ etalons contributes with an all-pass behavior having a group delay spectrum given by the Gires-Tournois characteristics [27],

![Fig. 1. Mobile optical fronthaul architecture that offloads beamforming to the centralized radio signal processing through integration of this function with opto-electronic (o/e) subsystems employed for analogue radio-over-fiber transmission between the BBU and the RRHs.](image-url)
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### TABLE I
EXPERIMENTAL BEAMFORMING DEMONSTRATIONS WITH CONTINUOUS DELAY SETTING

| Ref. | Year | Beamforming | Principle for TTD / phase shifter | Compactness / Requirements | Optical loss | Demonstrated frequency band | Delay range | Steering angle | Tuning speed |
|------|------|-------------|-----------------------------------|-----------------------------|--------------|-------------------------------|-------------|---------------|--------------|
| [6]  | 2018 | 1×8         | variable optical delay lines + multi-core fiber | fiber-optic delay line, requires multi-core feeder fiber | N/A | V band | ±16.6 ps | 30° | - |
| [7]  | 2018 | 1×2         | variable optical delay lines + multi-core fiber | fiber-optic delay line, requires multi-core feeder fiber | 3.5 dB | 50 GHz | 10 ps | 180° | - |
| [8]  | 2021 | 1×3         | WDM over single-mode fiber + coherent receiver | transistor-outline coherent receiver | 35.6 dB | 3.5 GHz | 930 ns | 20° | - |
| [9]  | 2015 | 4×4         | programmable optical filter | bulk-optic device | N/A | 25 GHz | 1.4 ns | - | - |
| [10] | 2005 | 1×4         | photonic crystal fiber | specialized-fiber-optics | 3.4 dB | X band | ±31 ps | 23° | - |
| [11] | 2017 | 1×8         | dispersion compensating fiber array | fiber-optic transmission spans as delay generator | N/A | 9.5 to 10.5 GHz | - | 43° | 12.5 ns |
| [12] | 2002 | 1×5         | tunable linear chirped fiber grating | fiber-optic grating | N/A | 20 GHz | 25 ns | - | <100 μs |
| [13] | 2020 | 1×4         | chirped fiber Bragg grating array | fiber-optic grating | N/A | X + Kλ bands | ±250 ps | ±36.8° | - |
| [14] | 2016 | 1×4         | chirped fiber Bragg grating in recirculating loop | fiber-optic grating, active recirculating loop | active loop | 11.2 GHz | 2.5 ns/τ | - | 60° | <1 ns |
| [15] | 2021 | 3×3         | raised cosine chirped fiber grating + Mach-Zehnder delay interferometer | fiber-optic grating | N/A | X band | 61 ps/λ | (70°, 124°) | - |
| [16] | 2016 | 8×8         | variable optical delay lines + chirped fiber Bragg grating | fiber-optic grating and delay line | N/A | 18 GHz | 16 ps | (50°, 300°) | - |
| [17] | 2021 | 1×8         | chirped fiber grating + polarization-maintaining dispersion compensating fiber | fiber-optic grating | N/A | 2.2 GHz | -100 ps/λ | 18° | - |
| [19] | 2014 | 1×10        | tunable dual Fabry-Perot etalon | multi-wavelength fiber ring laser with two Fabry-Perot etalons | N/A | 18 GHz | - | - | ±42° |
| [20] | 2022 | 2×5         | Gires-Tournois etalon | bulk-optic device | 5.3 dB | 3.5 GHz | 230 ps | 32° | 2 kHz |

\[ \tau_{gr}(\nu) = \sum_{N} \frac{2d}{c} \cdot \frac{1}{1 + R - 2\sqrt{R} \cos \left( \frac{4\pi d}{\lambda} \right)} \]  

or

\[ \tau_{gr}(\lambda) = \sum_{N} \frac{2d}{c} \cdot \frac{1}{1 + R - 2\sqrt{R} \cos \left( \frac{4\pi d}{\lambda} \right)} \]  

where \( c \) is the speed of light. This function yields a linear periodic evolution over the optical frequency \( \nu \) and approaches a sawtooth-like behavior with a large number \( N \) of etalons. Moreover, the period of the group delay function is adjusted to the dense wavelength division multiplexing (DWDM) spacing, meaning that the linear delay ramp repeats itself for each of the DWDM channels in a colorless manner.

The delay is set not through the etalon cascade, which remains passive, but through the injected optical frequencies. Since the optical source lasers can be precisely tuned with respect to their emission wavelength by either defining their temperature or current, this permits a continuous tuning of the group delay for each of the tributary channels that feed a single RRH. The robustness and accuracy of the spectral set-point is supported by the centralized approach for light generation, which permits

![Fig. 2. Photonic RF beamsteering integrated with analogue radio-over-fiber transmission and accomplished through a centralized etalon cascade.](image-url)
the use of integrated DWDM sources [28] and joint temperature control for the entire comb, thus ruling out source-by-source variations.

The spectral tuning of the emission wavelength translates into an element-by-element setting of the RF carrier phase and, consequently, enabling RF beamsteering by an angle $\theta$. In case of a linear phase evolution among the phase elements, which are spaced by the distance $\sigma$, this angle can be derived as

$$\theta = \arcsin \left( \frac{c \delta \tau}{\sigma} \right)$$

with $\delta \tau$ being the difference in group delay among two antenna elements.

The present work focuses on RF phase adjustment through the etalon cascade. Advanced beamforming schemes would require the adjustment of both, RF phase and amplitude, which could be simply accomplished by tuning the launch power of the DWDM comb wavelengths.

B. Characterization of the Etalon Cascade

Fig. 3 reports the C-band group delay dispersion for the etalon cascade used in the later experiment. The group delay is further being related to the optical transmission of an athermal arrayed waveguide grating used as DWDM demultiplexer at the RRH to implement the signal feed for all of its antenna elements. The group delay dispersion features a periodicity of 50 GHz. It is further centered to the nominal channel wavelength of the ITU-T G.694.1 DWDM grid and allows delay tuning within the transmission window of the demultiplexer. As Fig. 4 shows, a range from $-0.1$ to $0.13$ ns can be accommodated within the spectrally flat transmission window of a DWDM channel. As we will experimentally validate in Section V, this group delay dispersion makes the etalon cascade compatible with the RF phase-tuning requirements for phased-array antenna configurations for radio carrier frequencies in the sub-6GHz wireless band. Moreover, the wideband response of the etalon cascade and specifically its colorless nature enable its use as a centralized element. With this, it can be cost-shared among many antenna sites and further supports the notion for lean RRHs, for which RF and optical functions are ideally pooled at the CO that marks the head-end of the mobile fronthaul. On top of this, the loss associated to the beamformer element can be compensated through the booster amplifier employed to launch the feeder signal for the mobile optical fronthaul, which in case of a distributed integration at the RRH site could not be techno-economically justified.

Operation for higher RF carrier frequencies would require a re-design of the etalon cascade towards a wider periodicity. At the same time, the delay range should be reduced to relax the required accuracy for the spectral set-point that directly translates to the induced delay.

IV. EXPERIMENTAL SETUP

The experimental setup is presented in Fig. 5. It resembles a mobile fronthaul configuration with centralized beamsteering functionality integrated with the optical downlink transmitter, a RRH with a $2 \times 5$ configuration for its antenna elements, supplied through an analogue radio-over-fiber feed, and a short RF free-space propagation prior to the analysis of the received radio signal.

At the CO, a wavelength set $\lambda S1$ comprised of 10 DWDM channels ranging from $\lambda_1 = 1547.72$ to $\lambda_{10} = 1558.17$ nm is formed (Fig. 6). An orthogonal frequency division multiplexed (OFDM) radio signal with 128 sub-carriers featuring 64-ary
quadrature amplitude modulation (QAM) is generated by an arbitrary waveform generator (AWG). The OFDM signal has a bandwidth of 250-MHz and is centered at a radio carrier at $f_{RF} = 3.5$ GHz. The OFDM signal is modulated on all channels of the wavelength set by means of a Mach-Zehnder modulator (MZM) that is biased at its quadrature point. This first wavelength set will serve the evaluation of the radio signal transmission performance by means of off-line error vector magnitude (EVM) measurements.

Ten more DWDM channels within a second wavelength set $\lambda S2$ ranging from $\lambda_{11} = 1533.47$ to $\lambda_{20} = 1542.14$ nm (Fig. 6) are jointly modulated by another MZM, driven by a software-defined radio (SDR) unit. The SDR generates an OFDM signal at the same $f_{RF}$ with a bandwidth of 20 MHz and 64-QAM sub-carrier modulation at a code rate of 3/4. The transmission performance for this second radio signal will be evaluated in terms of real-time block error ratio (BLER) and involves either pseudo-random data or traffic due to high-definition video-transmission.

Either comb of modulated DWDM channels is then spectrally processed by the cascade of Gires-Tournois etalons (GTEC), determining the delay setting for the constituent radio signals of all antenna elements. The GTEC has an optical transmission loss of 5.3 dB, which is compensated by an Erbium-doped fiber amplifier (EDFA) that is boosting the launched optical power to a level of 3 dBm/λ, with an average optical signal-to-noise ratio of 36.7 dB/0.1 nm. It shall be stressed that the wavelength sets are feeding a single RRH alternatingly, meaning that they are not simultaneously transmitted in this work.

The optical distribution network (ODN) employs a variable optical attenuator ($\lambda_{att}$) to simulate a passive trunk split and to set the optical budget of the ODN. The feeder span of the fronthaul is emulated by a 12.8-km long, ITU-T G.652B compatible single-mode fiber (SMF).

An arrayed waveguide grating at the RRH distributes the received DWDM channels of a wavelength set to its $2 \times 5$ antenna elements. The allocation of the comb was the following: the lower row was fed by the channels 1-5 of the AWG-driven wavelength set $\lambda S1$, while the upper row is supplied through channels 6-10. For the SDR-driven wavelength set $\lambda S2$, channels 11–15 and 16–20 apply. It shall also be noted that multiple RRHs can be in principle operated simultaneously on different wavelengths set. This can be for example accomplished through a DWDM demultiplexer with free spectral range property and waveband pre-filtering. After demultiplexing, the radio signals are converted to the RF domain through 10-GHz PIN receivers with transimpedance amplifier (TIA) backend. An additional RF amplifier serves as power amplifier for each of the antenna elements. It shall be stressed that care must be taken to avoid a path-length mismatch in the optical and RF domain once the wavelength set is demultiplexed. However, the maturity of photonic integrated circuit technology permits the integration of the entire opto-electronic RRH interface on a single chip, thus mitigating any mismatch due to inaccurate cable lengths.

The phased-array transmit antenna of the RRH is arranged on a rotation platform, which allows to set the pointing angle $\alpha$ of the antenna plane, as required for the evaluation of the beam steering efficiency. Contrarily, the receive antenna at the mobile equipment (ME) is fixed with respect to its orientation, pointing towards the transmit antenna (Fig. 7). The receive antenna had a directional gain of 23 dB, which greatly supports the suppression of RF reflections upon free-space radio signal transmission. An RF spectrum analyser (RFSA) and a real-time oscilloscope were used to acquire the received RF power and the radio signal for the purpose of EVM estimation. Moreover, a second SDR unit has been used for real-time BLER measurement and video transmission. The uplink for the SDR units, which has not been in the scope of the present work, has been implemented through an electrical loop-back connection.
The RF phase adjustment per antenna element will practically require an auxiliary feedback channel to provide monitoring information on the actual RF phase setting, which can be easily acquired through a simple RF phase detector included with the RRH. This monitoring feature would further allow to mitigate the impact of dispersion at the feeder fiber, whose wavelength-dependent dispersion results in a small tilt in the RF phase setting among the antenna elements.

V. PHOTONIC RF BEAMSTEERING

The beamsteering functionality has been firstly evaluated by measuring the RF power for three different delay settings through the GTEC, which have been defined through the exact emission frequency set-point within the DWDM channel dedicated to the optical sources comprising the wavelength set. The chosen settings leading to a RF carrier phase shift of $\varphi = 0^\circ, 74^\circ$ and $150^\circ$ (at $f_{RF} = 3.5 \, \text{GHz}$) between consecutive horizontal antenna elements, which have been monitored by tapping the RF outputs of the PIN/TIA receivers. Elements in the same column of the phased-array transmit antenna feature the same carrier phase. Consequently, the beam is deflected in azimuth $\theta$. According to (2), the expected values for the aforementioned phase shifts are $\theta_e = 0^\circ, 20^\circ$ and $44^\circ$.

The acquired RF carrier at $f_{RF}$ is shown in Fig. 8 after photodetection at the RRH. The traces are listed for all DWDM channels belonging to the wavelength set $\lambda S1$ and for the case that the RF carrier remains unmodulated at the CO. The phase shift of $\varphi = 150^\circ$, introduced by the delay setting of the GTEC, is clearly visible. As mentioned before, the elements in the same column of the antenna (Ch.1 and Ch.6, Ch.2 and Ch.7, and so on, see Fig. 3) had the same group delay and amplitude, and different phase shifts were assigned among the columns, depending on the desired beam steering angle.

In order to retrieve the beam profile, we rotated the transmit antenna by an angle $\alpha$ while acquiring the received RF power at the stationary receive antenna. Fig. 7 relates the beam deflection angle $\theta$ and the rotation angle $\alpha$ to the experimental antenna setup.

Fig. 8 presents the resulting beam profiles and the induced beamsteering effect for the three different beam deflection angles $\theta_e$. For a phase shift of $\varphi = 0^\circ$, corresponding to an identical delay setting for all antenna elements, the main lobe points towards $\theta = -1^\circ$ (○) and has a full-width half maximum beam width of $12^\circ$. In this case, the power maximum is obtained when the antennas are facing each other. For the setting of $\varphi = 74^\circ$, the steering angle $\theta = 15^\circ$ (⋆), meaning that the transmit antenna needs to be rotated by an angle $\alpha = \theta$ to obtain maximum power transmission to the receive antenna. A setting of $\varphi = 150^\circ$ yields $\theta = 32^\circ$ (□). We noticed an error $\theta - \theta_e$ between theory and experiment and a slight widening of the main lobe for an increased $\theta$. Further investigations would require the use of an anechoic chamber in order to rule out RF fading effects due to reflections (see for example the asymmetry for $\varphi = 0^\circ$), leading to a more precise acquisition of the beam profile. We did not observe a degrading effect due to transmission over the feeder fiber of the mobile fronthaul.

VI. ANALOGUE RADIO TRANSMISSION PERFORMANCE

After evaluating the principal beamsteering functionality we proceeded to evaluate the radio signal transmission performance for wavelength set $\lambda S1$. The corresponding results are reported in Fig. 9. We conducted two different measurements: First, we investigated the impact of opto-electronic signal conversion by acquiring the radio signals at one of the RRH elements after photodetection. Second, we acquired the radio signal after phased-array RF propagation.

Fig. 9(a) shows the received RF spectra. Just after photodetection of the optically hauled radio signal, which is received at an optical power of $-8 \, \text{dBm}$, the OFDM spectrum has a flat envelope. This confirms that there is no bandwidth degradation introduced by the GTEC. The corresponding EVM, presented in Fig. 9(b), has an average EVM of $6.7\%$ (⦁) at this optical feed level.

There were no RF interference fringes observed after RF phased-array propagation between transmit and receive antennas (Fig. 9(a)), owing to their good directional characteristics that suppress multi-path interference. Nevertheless, the roll-off in RF power towards higher frequencies is attributed to the fading inherent to RF propagation. We further noticed the effect of the phased-array gain through a slightly improved EVM of $5.9\%$ (Fig. 9(b), ⦁). The tilt in EVM performance towards higher values for a higher sub-carrier index is associated with the aforementioned fading.

The EVM dependence on the optical budget between CO and RRH is presented in Fig. 9(c). Results are again reported for the received radio signal at one antenna element. For the employed PIN/TIA receiver, the EVM antenna limit of $8\%$ for 64-QAM transmission is reached at a received optical power of $-9.8 \, \text{dBm}/\lambda$. A better sensitivity could be accomplished through the use of avalanche photodetectors, which would further permit a higher dynamic range for simultaneous RF amplitude and phase adjustment in advanced beamforming schemes.

Fig. 9(d) reports the EVM after RF propagation as function of the rotation angle $\alpha$ of the transmit antenna and relates it to the received RF power acquired earlier in Section V. Results are shown for the beamsteering setting yielding $\theta = 15^\circ$, corresponding to Fig. 8(b). The EVM (⦁) evolves over $\alpha$ in a way that closely matches the received RF power and shows a minimum for $\alpha \approx \theta$. The clean 64-QAM constellation for
Fig. 8. Resulting beam profiles for (a) $\varphi = 0^\circ$, (b) $\varphi = 74^\circ$ and (c) $\varphi = 150^\circ$, with expected deflection angles $\theta_e = 0^\circ$, $20^\circ$ and $44^\circ$, respectively. The exemplary RF carrier signals for the $2 \times 5$ phased-array antenna after photodetection of the wavelength set $\lambda S1$ at the RRH are shown for a configuration of $\varphi = 150^\circ$.

Fig. 9. (a) Received OFDM radio signal spectra before and after phased-array RF propagation and (b) Corresponding EVM for an optical feed of $-8$ dBm. (c) EVM after photodetection, as function of the received optical power. (d) EVM and RF power after phased-array RF propagation for a setting of $\theta = 15^\circ$.

Fig. 10. BLER as function of the transmit antenna rotation. Results and constellations diagrams are shown for a beamsteering setting of $\theta = 15^\circ$.

VII. REAL-TIME SDR-BASED EVALUATION

Next, we have conducted real-time measurements of the BLER and conducted high-definition video streaming at $1920 \times 1090$ px$^2$ using the second RRH feed at the wavelength set $\lambda S2$, which is driven by the SDR unit.

Fig. 10 relates the measured BLER ($\bullet$) for a beamsteering setting of $\theta = 15^\circ$ to the corresponding received RF power of Fig. 8(b). Measurements are reported for an OFDM radio signal modulated by pseudo-random data as function of the rotation angle $\alpha$ for the transmit antenna. The RF loss budget had been artificially increased in order to obtain error-free conditions only for the maximum received RF power at the center of the main lobe. In this way, the effect of an angular misalignment can...
be evaluated without being subject to BLER clipping effects. We found a good agreement for the rotation angles beyond $\alpha = \theta$ along the main lobe of the antenna beam, while the rapid decrease in BLER for decreasing $\alpha$ could not be elucidated. The constellations presented Fig. 10, obtained through real-time OFDM demodulation, show the increase in BLER associated with the power drop inherent to a walk-off from the main beam lobe.

Fig. 11 presents long-term measurements of received RF power at the SDR unit of the ME, the associated BLER and the data throughput when streaming the video for more than one hour. The received power in Fig. 11(a) resembles a burst-like behavior, which resembles the idling periods of the SDR transmitter upon a partially loaded OFDM link. The corresponding data throughput with its burst-like behavior is included in Fig. 11(b). It features an average load of 5.8 Mb/s as required for video streaming. The resulting spread in received RF power is reported in Fig. 11(c) and indicates a stable received power for an active SDR transmitter. More importantly, the BLER, shown in Fig. 11(b), remains at an error-free level for the entire duration. We have not observed visual artifacts observed for the received video feed.

VIII. RF CARRIER PHASE SWITCHING

Mobility of users in beam-centric radio communication schemes or the provision of beams targeting multiple users might require a fast reconfiguration of the antenna beam. This necessity translates to a fast switching of the RF carrier phase.

To investigate this response of the proposed beamforming concept to this requirement, we introduced fast switching of the RF carrier phase through direct chirp modulation of the distributed feedback (DFB) laser associated to the DWDM feed channel at $\lambda_1 = 1547.72$ nm. The frequency modulation of the DFB emission, introduced through bias current modulation, amounts to 1 GHz/mA and is subsequently converted to a RF carrier phase change by the GTCE.

We synchronized the optically introduced RF carrier phase modulation with the generation of OFDM radio packets. Fig. 12 shows the DFB drive and the skew-corrected received OFDM packets after photodetection at the RRH. The phase switching frequency was 2 kHz and a gap of 50 $\mu$s has been inserted between two OFDM packets with relatively shifted RF carrier phase ($\varphi_1, \varphi_2$) to account for phase transitions between the packets.

Fig. 13 presents the constellations for both OFDM packets ($\varphi_1, \varphi_2 = \varphi_1 + \Delta \varphi$) of a frame for the two peak-to-peak DFB modulation swings of $I_{\text{mod}} = 2 \text{ mA}_{\text{pp}}$ and 10 mA$_{\text{pp}}$. The received OFDM constellations are characterized by the position of the pilot tone $\pi$, which is used as an indicator for the introduced RF carrier phase shift. The relative alignment between the RF carrier phases of the two OFDM packets is yielded with $\Delta \varphi = 7$ and 35°. This result further underpins the efficiency of the RF phase switching, which can be accomplished without extra components and at rather low drive levels.

In order to validate that the EVM performance is not impacted negatively, the EVM has been estimated for both OFDM packets. The corresponding EVM per subcarrier is presented in Fig. 14 for the first (■) and second (▲) OFDM packet. The difference in the average EVM between the two OFDM packets was 0.4%,
confirmed the error-free operation through long-term measurements involving high-definition video transmission. Finally, we have evaluated fast RF carrier phase switching for one of the antenna elements through direct emission frequency modulation at 2 kHz, proving the concept to be compatible with deployment scenarios involving the tracking of mobile users at high velocity.

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Fig. 13. RF carrier phase shifts for 64-QAM OFDM radio signal transmission at different DFB modulation settings.

Fig. 14. EVM performance for the two OFDM packets with switched RF carrier phase.

which proves that the DFB current modulation for RF carrier phase switching does not introduce a penalty in the RF signal transmission.

Even though the switching of the RF carrier phase has not been applied to all antenna elements, it proves that the GTCE supports fast beamsteering in principle.

IX. CONCLUSION

An all-optical method for centralized RF beamsteering has been demonstrated in combination with a simplified RRH employing a 2×5 phased-array antenna configuration. The proposed concept builds on a GTEC with periodic group delay dispersion, making it compatible with DWDM overlay schemes and a per-element delay setting exploiting emission frequency tuning of the involved DWDM channels. For this purpose, the GTEC has been shown to adhere to the ITU-T DWDM grid and has enabled remote beamsteering of up to 32°. A good radio signal transmission performance has been validated through both, offline EVM measurements for a 250-MHz 64-QAM OFDM radio signal at 3.5 GHz. Measurements without and with beamsteering have proven that no penalty is introduced through the beamsteering concept, while the EVM performance agrees well with the expected beam profiles upon applied beam deflection. Real-time measurements supported by SDRs have
J. Opt. Soc. Korea (Graduate Student Member, IEEE) was born in 1997, in Spain. In 2012 to 2015, he worked for the Institute of Telecommunications, implementing a software defined radio based cell-free massive MIMO testbed and ongoing applied research projects on a national and international scale. He was elected as a Board-of-Stakeholder Member of the Photonics21 European Technology Platform in 2017, and is a Technical Program Committee member for the ECOC and OFC conferences. During his extensive research activities, he was/is still engaged in several European projects, such as SARDANA, BONE, BOOM, APACHE, GALACTICO, EURO-FOS, and the Quantum Flagship project UNIQORN. In 2011, he joined the Photonic Communications Research Laboratory, National Technical University of Athens, Greece, as a Postdoctoral Researcher and established his research activities on coherent FTTH under the umbrella of the FP7 GALACTICO project. In 2013, he established his own research force on photonic communications with the AIT Austrian Institute of Technology, Vienna, Austria, where he is working toward next-generation metro-access-5G networks, photonics integration technologies, and quantum optics. He has authored or coauthored about 190 publications in top-tier conferences in the field of OFC and ECOC.

Thomas Zemen (Senior Member, IEEE) received the Dipl.-Ing. degree in electrical engineering, the Doctoral degree, and the Venia Docenti (Habilitation) from the Vienna University of Technology, Vienna, Austria, in 1998, 2004, and 2013, respectively. He is currently a Principal Scientist with the AIT Austrian Institute of Technology, Vienna, Austria, leading the Reliable Wireless Communications Group. Previously he was with Telecommunication Research Center Vienna (FTW) and Siemens Austria. He is the author or coauthor of four books chapters, 39 journal papers, and more than 118 conference communications. His research interests include the interaction of the physical-radio communication channel with other parts of a communication system for time-sensitive 5G and 6G applications. Dr. Zemen is a Docent with the Vienna University of Technology, and was the Editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS from 2011 to 2017.

Bernhard Schrenk (Member, IEEE) was born in 1982, in Austria. He received the M.Sc. degree in microelectronics from the Technical University of Vienna, Austria, in 2007, and the Ph.D. degree from UPC BarcelonaTech, Barcelona, Spain, in 2011. He was with the Institute of Experimental Physics of Prof. A. Zeilinger, where he was involved in the realization of a first commercial prototype for a quantum cryptography system, within the European SECOQC project. His Ph.D. thesis on multifunctional optical network units for next-generation fiber-to-the-home access networks was carried out within the FP7 SARDANA and EURO-FOS projects. In 2011, he joined the Photonic Communications Research Laboratory, National Technical University of Athens, Athens, Greece, as a Postdoctoral Researcher and established his research activities on coherent FTTH under the umbrella of the FP7 GALACTICO project. In 2013, he established his own research force on photonic communications with the AIT Austrian Institute of Technology, Vienna, Austria, where he is working toward next-generation metro-access-5G networks, photonics integration technologies, and quantum optics. He has authored or coauthored about 190 publications in top-of-the-line (IEEE, OSA) journals and presentations in the most prestigious and highly competitive optical fiber technology conferences. Dr. Schrenk was awarded with the Photonics21 Student Innovation Award and the Euro-Fos Student Research Award for his Ph.D. thesis, honoring not only his R&D work but also its relevance for the photonics industry. He was elected as a Board-of-Stakeholder Member of the Photonics21 European Technology Platform in 2017, and is a Technical Program Committee member for the ECOC and OFC conferences. During his extensive research activities, he was/is still engaged in several European projects, such as SARDANA, BONE, BOOM, APACHE, GALACTICO, EURO-FOS, and the Quantum Flagship project UNIQORN. In 2013, he was the recipient of the European Marie-Curie Integration Grant WARP-5. In 2018, he was awarded by the European Research Council with the ERC Starting Grant COYOTE, which envisions coherent optics everywhere.