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Phase Compensated Optical Fiber Based Ultra-Wideband Channel Sounder

Allan Wainaina Mbugua, Wei Fan, Kim Olesen, Xuesong Cai and Gert Frølund Pedersen

Abstract—In this paper, a novel vector network analyzer (VNA) based ultra-wideband (UWB) channel sounder using radio-over-fiber (RoF) techniques is presented. Benefiting from the usage of optical fiber cable, the measurement range, and dynamic range are increased significantly compared to the conventional coaxial based VNA system. Specifically, using RoF increases the dynamic range to a maximum of 112 dB at 30 GHz for the back to back connection with an optical fiber cable of length 300 m. Moreover, a state-of-the-art phase compensation scheme using optical circulators is proposed for the first time. The novel scheme renders the channel sounder immune to stochastic phase changes in the optical fiber cable due to thermal changes and mechanical stress thus permitting the remoting of virtual antenna arrays. The proposed channel sounder is experimentally validated in back to back measurements, anechoic chamber and practical indoor scenarios. The indoor channel measurements are conducted using a virtual uniform rectangular array (URA) at the millimeter-wave (mm-wave) band from 26.5 GHz to 30 GHz. The measured results demonstrate the developed channel sounder’s capability to perform UWB large-scale antenna array measurements with long measurement range.

Index Terms—5G, channel sounding, millimeter wave, radio propagation, radio-over-fiber, virtual antenna array.

I. INTRODUCTION

THE DWINDLING spectrum resource at the sub-6 GHz bands has led to an upsurge in the recent research interest at millimeter-wave (mm-wave) bands which will be the potential carrier frequencies for the fifth generation (5G) cellular network [1]. The 5G cellular network is expected to offer 1000 times (1000x) increase in the aggregate data rate to what is currently offered in the fourth generation (4G) cellular network [2]. To achieve this target, accurate channel characterization and modeling are fundamental for 5G system development and performance evaluation [3], [4]. This has subsequently led to the development of a plethora of channel sounders since the intricate nature of the radio channel makes it unfeasible to develop a channel sounder able to meet all sounding requirements [5].

Generally, channel sounders reported in the literature are based either on time domain or frequency domain techniques [6]. Correlation-based channel sounders [7]–[12] are an example of time domain based systems. One of the techniques utilized in these sounders to extract the channel impulse response (CIR) is the transmission of pseudo-random noise (PN) sequences that are robust to noise [13]. For channel sounders working in the frequency domain, a frequency sweep over the band of interest is usually performed and then the CIR is obtained by an inverse discrete Fourier transform of the measured channel frequency response (CFR).

One of most popular frequency domain technique has been the use of the vector network analyzer (VNA). The VNA has been widely used in static channel measurements due to its ability to perform a frequency sweep over a large bandwidth, ease of calibration and low cost [14]–[17]. Nonetheless, channel sounding with the VNA suffers two major limitations. First, the channel must be kept static in the time duration of the frequency sweep. To obtain a higher signal to noise ratio (SNR), narrower intermediate frequency (IF) bandwidth settings are desirable that result in an increase in the frequency sweep time. For this reason, the VNA is constrained to channel sounding in time-invariant channels [18], [19]. The second limitation is that the VNA setup requires a cable connection between the transmitter (Tx) and receiver (Rx) to remote the antennas and for phase synchronization. Since the signal attenuation per unit length in coaxial cables increases with increase in frequency [20], the measurement range is constrained to a few meters at mm-wave frequencies while the system dynamic range is also reduced. Consequently, the VNA based channel sounder has mainly been used for short-range deployment scenarios, e.g. indoor.

Several solutions to mitigate the signal loss in the coaxial cables in VNA based channel sounders have been proposed in the literature. In [21]–[23], a low noise amplifier (LNA) is added to the Rx chain, and a radio frequency (RF) power amplifier is added to the Tx chain to improve the signal dynamic range. To minimize signal loss in the RF chain and effectively increase the system dynamic range, a novel technique addressed in the literature is the application of the heterodyne principle. This involves the use of frequency up-converters close to the Tx antennas and down-converters at the Rx antennas. The transmission of a lower frequency IF or local oscillator (LO) signal in the coaxial cables results in lower signal loss compared to transmitting the RF signal in the coaxial cables. For example in [24], the Rx signal is down-converted to a lower frequency IF signal that is transmitted in the coaxial cables enabling the extension of the physical measurement range at mm-wave bands. In [25], the frequency sweep in the VNA is performed at a lower frequency which is up-converted at the Tx for over-the-air transmission at 60 GHz and subsequently down-converted at the Rx. In channel measurements above 100 GHz, the VNA
and frequency extender modules are used [26], [27], which are based on the principle of up-conversion and down-conversion of the RF signal. In [28], [29], signal loss in the coaxial cables is mitigated by transmitting the signal from a signal generator that is synchronized with a VNA, where the Rx signal is recorded.

To increase the VNA measurement range, an alternative solution is to exploit radio-over-fiber (RoF) techniques where the signal loss in the coaxial cables can be resolved by the use of electrical-to-optical (E/O) and optical-to-electrical (O/E) units and optical fiber cables [30]–[32]. The optical fiber transmission lines have the advantage of low signal loss e.g. 0.4 dB/km for single mode optical fiber cable which corresponds to 0.8 dB/km in the RF domain [33]. This is a significant improvement over ultra-low loss performance RF coaxial cables that can incur signal loss e.g. 1.59 dB/m at 30 GHz. Despite the low loss properties of optical fiber cables, they are inherently sensitive to phase change due to thermal and mechanical stress [34], [35]. This implies that the RoF technique is not suitable for use in conjunction with virtual antenna arrays and has typically been used for power measurements [32]. This is a significant limitation since coherent and accurate phase measurements are pivotal to obtain the spatial profile of the multipath components (MPC).

In [36], phase coherent measurements are reported using RoF, where the LO signal is distributed to the down-converter and up-converter via optical fiber cables. Nonetheless, the phase correction details of the channel sounder are not reported. Similarly, phase coherent measurements are reported in [31] at 5.25 GHz and in [37] at 5 GHz with no details of the phase stability of the channel sounders. Moreover, the RF signal modulating the optical carrier in these cases is in the sub-6 GHz range where phase errors due to the optical fiber could be small relative to the wavelength.

To enable phase-coherent long range channel sounding measurements for ultra-wideband (UWB) systems with the VNA using RoF techniques, two phase correction strategies were proposed and discussed briefly by the authors in [38]. The bidirectional scheme was shown to be effective in mitigating the phase change due to thermal and mechanical stress. In this paper, the principle of the method introduced in [38] will be further explained with both theoretical analysis and experimental validations. The optical carrier is modulated by an RF signal both in the sub-6 GHz and mm-wave frequency range. A novel phase compensation mechanism is implemented using two 3-port optical circulators. The underlying concept of this novel technique is to have bidirectional signal transfer on the same optical fiber cable where the signal to the Tx antenna is fed back to the VNA. Using the feedback signal, the impairments that are introduced by the optical fiber cable can then be de-embedded from the channel measurements. In addition to the phase compensation, a dynamic range of 112 dB is attained for the back to back setup due to the significant reduction of signal loss as a result of the RoF technique. To the best of the authors’ knowledge, this is a first of a kind VNA based channel sounder employing the novel phase compensation mechanism using optical circulators.

The rest of the paper is organized as follows. Section II outlines the channel sounder’s architecture, Section III contains the details of the validation measurements, Section IV outlines the measurement campaigns in realistic propagation environments and finally, Section V concludes the paper.

II. CHANNEL SOUNDER ARCHITECTURE

At the heart of the channel sounder shown in Fig. 1 is the VNA with the capability of performing a frequency sweep from 10 MHz to 67 GHz. An optical fiber link with a frequency range of 1 GHz to 50 GHz is used for remoting the Tx antenna.

The optical fiber link is composed of a transmitter, which is an externally modulated laser with a center wavelength of 1550 nm and two receivers (photo-detector), one for the forward link and the other for the feedback link shown in Fig. 2. The optical fiber link has pre and post-amplification stages with a gain that varies from 12 dB at 1 GHz to -18 dB at 50 GHz at room temperature. The optical fiber link has a noise figure of 11 dB at 1 GHz and the maximum is 31 dB at 45 GHz. However, the noise figure is relatively flat with a value of 18 dB in the frequency band between 25 GHz and 30 GHz.

A one-to-two optical power splitter is used to divide equally the optical power between the forward and feedback links which results in an RF power loss of 6 dB at each port. Two non-polarization maintaining 3-port optical circulators are used to enable bidirectional signal transmission on the same single mode optical cable of length 300 m. The bidirectional signal transmission on the same optical fiber cable is attained by exploiting the non-reciprocity property of the optical circulators which have a peak isolation of 40 dB between port T and port R shown in Fig. 1, thus signals in the forward and feedback link are sufficiently isolated. The non-polarization maintaining optical circulators enable the use of a non-polarization maintaining single mode optical fiber cable which is less expensive and has lower attenuation compared to a polarization maintaining optical fiber cable. An RF amplifier with a frequency range of 26.5 GHz to 40 GHz, a gain of 40 dB, a noise figure of 6.2 dB and a 1 dB compression point of 20 dBm is used after the O/E stage before the signal is fed to the Tx antenna. A suitable heat sink is added to maintain the thermal stability of the RF amplifier, as shown in Fig. 2. The cascade of the amplification by the optical fiber link and the RF amplifier results in a total noise figure of 18.3 dB at 30 GHz. The channel sounder’s components are outlined in Table I.

A. Principle of Operation

In VNA based channel measurements, the radio channel is considered the device under test (DUT), and the CFR can then be obtained from the measured scattering parameter (S-parameter). In conventional coaxial based VNA based systems, a normalization procedure is usually carried out to de-embed the frequency response of the cables. The basic assumption behind the normalization procedure is that the frequency response of the cables is time-invariant. However, when using optical fiber cables subtle changes in temperature and mechanical stress can cause a significant phase variation
which results in a large deviation from normalization. This can result in significant errors in the measured CFR. To mitigate these errors, a feedback link is necessary to record the signal drift caused by the optical fiber cable. Optical circulators enable bidirectional signal transmission on the same optical fiber cable, hence the forward link and the feedback link can use the same cable as illustrated in Fig. 1.

The forward and feedback links are recorded in the VNA as the S-parameters $S_{21}(f)$ and $S_{41}(f)$ respectively. After normalization in the back to back setup, the frequency response of the forward ($S_{21}(f)$) and feedback ($S_{41}(f)$) links are both equal to one. Replacing the back to back connection with suitable antennas, the CFR, $H(f)$ can be recorded in $S_{21}(f)$ as

$$S_{21}(f) = 1 \cdot H_{fw}(f) \cdot H(f)$$  \hspace{1cm} (1)

The error term $H_{fw}(f)$ is due to the mechanical stress and

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**TABLE I**

CHANNEL SOUNDER’S COMPONENTS

<table>
<thead>
<tr>
<th>Part</th>
<th>Name</th>
<th>Frequency/Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNA</td>
<td>Keysight PNA N5227A</td>
<td>10 MHz to 67 GHz</td>
</tr>
<tr>
<td>Optical power splitter</td>
<td>JDS Uniphase FFC-CKH12B105-003</td>
<td>1550 nm</td>
</tr>
<tr>
<td>RF amplifier</td>
<td>Cernex CBM26402520</td>
<td>26.5 GHz to 40 GHz</td>
</tr>
<tr>
<td>RF attenuator</td>
<td>Pasternack PE7090-20</td>
<td>DC to 40 GHz</td>
</tr>
<tr>
<td>Laser</td>
<td>Linear Photonics QMOD XMTQ-C-A-24</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Photo detector</td>
<td>Linear Photonics QMOD XMRQ-C-A-24</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Optical circulator</td>
<td>OZ optics FOC-12N-111-9/125-SSS-1550-55-SCASCASCA-1-1</td>
<td>1550 nm</td>
</tr>
</tbody>
</table>
thermal changes on the optical fiber cable. Similarly, for the feedback link, the error term \( H_{fb}(f) \) is embedded in the measured S-parameter \( S_{41}(f) \) as

\[
S_{41}(f) = 1 \cdot H_{fb}(f)
\]

(2)

The bidirectional signal transfer on the same cable implies that the signal in the feedback link has undergone twice the phase change in the forward link due to mechanical stress and thermal changes on the optical fiber cable. The frequency response \( H_{fb}(f) \) can thus be written as

\[
H_{fb}(f) = H^2_{fw}(f)
\]

(3)

In practical VNA measurements, the phase of the complex frequency responses \( S_{21}(f) \) and \( S_{41}(f) \) are usually wrapped e.g. in the interval \([-\pi, +\pi]\) radians. The phase \( \beta_{41} \), of the complex frequency response \( S_{41}(f) \) is unwrapped to obtain \( \phi_{41} \). The unwrapped phase, \( \phi_{41} \) is divided by 2 and wrapped back to the interval \([-\pi, +\pi]\) radians to obtain \( \psi_{41} \). Consequently, the error term \( H_{fw}(f) \) can be de-embedded from the CFR, \( H(f) \) as follows

\[
H(f) = \frac{S_{21}(f)}{\sqrt{|S_{41}(f)| e^{j\psi_{41}}}}
\]

(4)

B. Link Budget

The system link budget at 30 GHz for the back to back connection is illustrated in Fig. 3. The VNA Tx power is set to -12 dBm which gives a safe margin of 1 dB from the 1 dB compression point of the laser. After the E/O conversion stage, the optical signal for the forward link and the feedback link are isolated from each other using a pair of optical circulators. The optical circulators have an associated insertion loss that results in a total RF signal penalty of 4.3 dB. The optical power splitter, on the other hand, causes an RF power degradation of 6 dB. Phase compensation thus comes at a cost of approximately 10.3 dB signal loss for the forward link.

The power at the output of the O/E stage is -30 dBm which is not sufficient for channel sounding purposes particularly at the mm-wave band where the free space loss is quite high. An RF amplifier with a 40 dB gain is employed which boosts the signal power to 9.8 dBm. In the Rx chain, the 0.1 dB receiver compression at test port 2 of the VNA is 10 dBm. To avoid driving the receiver at test port 2 into compression, an RF attenuator of 20 dB is used during the calibration process and later de-embedded in post-processing. The obtained dynamic range is thus 112 dB for the back to back connection at 30 GHz. Note that the noise floor of the VNA is specified for an IF bandwidth of 10 Hz and is subject to change depending on the IF bandwidth setting.

III. CHANNEL SOUNDER VALIDATION

The channel sounder is validated using back to back measurements and over-the-air tests using omni-directional antennas in an anechoic chamber. The purpose of the back to back test is to test the amplitude and phase stability under two scenarios:

- Cable bending/mechanical stress.
- Thermal change/signal drift over time.

Amplitude and phase stability are fundamental if the channel sounder is to faithfully record the characteristics of the channel. Instability in the amplitude can lead to a false impression of frequency selective fading in a channel [39], whereas phase instability leads to errors in the angle of arrival (AoA) estimation when using virtual antenna arrays. On the other hand, over-the-air tests in the anechoic chamber are used to validate the whole measurement system including Tx and Rx antennas.

A. Cable Bending

In practical virtual antenna array measurements, mechanical stress on the optical fiber cable is inevitable due to the movement of the antenna positioning stages. To characterize the cable bending, the optical fiber cable is mounted on the turn-table used for virtual uniform circular array (UCA) measurements shown in Fig. 4. The turn-table with a radius of 0.5 m is rotated 720 steps to make a virtual circle where each step corresponds to a 0.5 degrees movement in the virtual circle. For example when the rotating arm is at the 60-th step as illustrated in Fig. 4, this corresponds to a 30 degrees movement in the virtual circle. In this way, different cable bending effects that would be experienced in practical virtual UCA measurements are mimicked and the frequency response is recorded at each step. In this case, the system is modified to exclude the RF amplifier shown in Fig. 1 to allow characterization of the phase characteristic of the optical fiber link from 1 GHz to 30 GHz. The phase is then measured at the calibration reference shown in Fig. 1. Note that before the measurement an initial normalization procedure is carried out for the back to back connection. This effectively shifts the phase reference plane from the VNA ports to the calibration reference plane illustrated in Fig. 1.

Mechanical stress essentially results in a change of the effective length of the optical fiber cable. The change in the
effective length of the optical fiber cable results in a phase change that is directly proportional to the frequency. This can be observed in Fig. 5 where the lower frequencies experience a smaller phase change compared to the higher frequencies as the turn-table moves along the 720 points of a circle. The gradient of the linear phase response varies at every step of the turn-table meaning that at each step the effective length of the optical fiber cable is different. Since the bending of the optical fiber cable is rather stochastic, its effective length at different steps is also random as shown in Fig. 5. Nonetheless, the phase change at each step for the forward link in Fig. 5a is observed to be half that of the feedback link in Fig. 5b at each frequency point from 1 GHz to 30 GHz. After the phase compensation, the phase deviation due to cable bending is maintained within 2.5 degrees at 30 GHz as illustrated in Fig. 5c.

B. Signal Drifting Over Long Measurement Time

Signal drift over long measurement time is highly likely in practical measurement due to thermal drift of the measurement system and in particular the optical fiber cable. Virtual antenna array measurements involving large-scale elements (i.e. measurements over many spatial points) can span several hours to record one channel snapshot. Besides keeping the channel static, it is also crucial that the measurement system has no signal drift or the signal drift is insignificant during the entire measurement period. However, subtle changes in the ambient temperature have been reported in the literature to cause significant phase change of the signal propagating in the optical fiber cable [34], [35]. To verify the robustness of the system to the phase change on the optical fiber cable due to an ambient temperature change, a back to back measurement using the circuit in Fig. 1 is carried out. A 20 dB attenuator is included in the back to back setup to keep the signal level into the VNA receiver at test port 2 below the 0.1 dB compression point. The VNA and the RF amplifier are turned on for at least 30 minutes before a normalization procedure is carried out for both the forward and the feedback link. A frequency sweep is then performed continuously for a period of 17 hours, during
which data is saved every fifth minute due to data storage constraints. During this period the channel sounder is kept stationary in a secured room to ensure no movement on the optical fiber cable occurred due to personnel. The room has standard air conditioners to maintain the ambient temperature at a predefined level. Nonetheless, a variation of more than 1°C would occur, mainly due to heat generated by the VNA over the long measurement period, which can cause significant phase change on the 300 m long optical cable [34], [35].

The phase of the channel sounder with the RF amplifier is shown in Fig. 6. In the forward link, the phase can be observed to vary over 50 degrees at 30 GHz as shown in Fig. 6a. In the feedback link, the phase change can be seen to be twice that in the forward link as shown in Fig. 6b. The phase compensation is then performed using (4). The compensated phase for a period of 17 hours can be seen to be maintained within 2.5 degrees at 30 GHz as shown in Fig. 6c. This demonstrates the robustness of the phase compensation mechanism using the optical circulators.

The amplitude which is computed as the absolute square of the frequency response is shown in Fig. 7. The amplitude varies by approximately 0.2 dB for the measurement in the first half hour. After 30 minutes the amplitude stabilizes and the variation is less than 0.1 dB for the next 16 and a half hours. Overall, the amplitude of the system was observed to be very stable as shown in Fig. 7.

C. Anechoic Chamber Measurements

To evaluate the system, over-the-air measurements are carried out in an anechoic chamber as shown in Fig. 8. At the Tx and Rx, vertically polarized biconical antennas with omnidirectional radiation patterns in the azimuth are employed. The Tx antenna has an operation frequency of 1.5 GHz to 40 GHz [40] whereas the Rx antenna (AINFO-SZ-2003000/P) has an operation frequency of 2 GHz to 30 GHz. A virtual uniform rectangular array (URA) made of 900 virtual antenna elements (i.e. 30×30) with an inter-element spacing of 0.4λ at 30 GHz is implemented at the Tx by moving the Tx antenna along predefined positions in space. The movement of the Tx antenna is optimized to reduce measurement time by moving along the x-axis for a fixed position of the y-axis. At the end of the x-axis, the antenna positioning stages shift to the next y-axis position and reverse along the x-axis. This process is repeated until all the positions in space are covered to create the virtual URA which takes a total of 2 hours. A summary of the measurement parameters is outlined in Table II.

In the anechoic chamber measurements, the Tx and Rx antennas are separated by 212 cm. In an ideal situation, the propagation channel should consist only of the line-of-sight (LOS) path. However, this is not the case due to imperfection in the chamber and reflections from the measurement equipment. Nonetheless, the power level of the reflections is 30 dB below the LOS component as shown in the power angle delay profile (PADP) in Fig. 9.

The phases of the channel coefficients across the different URA elements at a fixed frequency point can be extracted from the measurement data for the LOS component using the space-alternating generalized expectation-maximization (SAGE) algorithm [41]. Specifically, the generic model of the CIR observed at the m-th element of the antenna array is formulated.

![Fig. 6. Unwrapped phase of the channel sounder with the RF amplifier included over a period of 17 hours. (a) Phase of the forward link, (b) phase of the feedback link and (c) compensated phase.](image-url)
Table II: Measurement parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNA Tx power</td>
<td>-12 dBm</td>
</tr>
<tr>
<td>IF bandwidth</td>
<td>5 KHz</td>
</tr>
<tr>
<td>Frequency</td>
<td>26.5 GHz to 30 GHz</td>
</tr>
<tr>
<td>Frequency points</td>
<td>6000</td>
</tr>
<tr>
<td>Frequency step</td>
<td>583.431 KHz</td>
</tr>
<tr>
<td>Sweep time</td>
<td>2.03 s</td>
</tr>
<tr>
<td>Tx and Rx antenna height</td>
<td>1.61 m</td>
</tr>
<tr>
<td>Virtual URA dimensions</td>
<td>11.6 cm × 11.6 cm</td>
</tr>
</tbody>
</table>

Fig. 9. PADP of the measurement in the anechoic chamber with a dynamic range of 30 dB. The color bar represents power in dB.

where \( L \) represents the path number, \( \alpha_{m,\ell} \) denotes the complex amplitude of the \( \ell \)-th path, \( \tau_{m,\ell} \) is the propagation delay of the \( \ell \)-th path, \( \delta(\cdot) \) denotes the Dirac delta function, and \( n(\tau) \) represents the noise. By exploiting the SAGE principle, \( \alpha_{m,\ell}'s \) and \( \tau_{m,\ell}'s \) can be obtained from the measured data for individual array elements. Readers are referred to [41] for the details of the SAGE principle. Since in the anechoic chamber the LOS path is always with the maximum power and minimal propagation delay, the LOS amplitude \( \alpha_{m,\text{LOS}} \) and LOS delay \( \tau_{m,\text{LOS}} \) can be easily identified. With the estimated \( \alpha_{m,\text{LOS}} \) and \( \tau_{m,\text{LOS}} \), the channel transfer function at the \( m \)-th antenna contributed by the LOS path only can be reconstructed as

\[
H_m(f) = \alpha_{m,\text{LOS}} \exp(-j2\pi f \tau_{m,\text{LOS}}) \tag{6}
\]

Consequently, the phase shift of the LOS path across the array can be obtained by checking the reconstructed channel transfer functions, and the propagation distance can be calculated according to \( \tau_{m,\text{LOS}}'s \). The theoretical propagation distance from each antenna element of the virtual URA to the Rx antenna is then compared to the actual measured distance, where a good match is attained as shown in Fig. 10. Fig. 11a illustrates the comparison between the empirical LOS phase shifts and the theoretical LOS phase shifts at 30 GHz across the array. The phase shift across the array can be observed to correspond to the movement of the antenna array positioning stages. The shift to the next \( y \)-axis position and the reverse motion along the \( x \)-axis can be observed for example after the 30-th antenna index. The empirical and theoretical phase shift across the array match well indicating the robustness of the system. The phase deviation between the empirical and the theoretical value shown in Fig. 11b is most likely introduced by errors in the geometrical alignment of the antennas.
IV. CHANNEL MEASUREMENTS

A. Measurement Campaigns

Measurement campaigns are carried out in two realistic indoor propagation scenarios in the LOS with the measurement parameters outlined in Table II.

- Short-range measurements in the front of an auditorium.
- Long-range measurements in a corridor environment.

The short-range measurement scenario is illustrated in Fig. 12. The Tx and Rx antennas are separated by 5.8 m. Behind the Tx antenna is glass window whose curtain had been closed during the measurement. The long-range measurement is carried out in a corridor environment where the Tx and Rx are separated by 46 m as shown in Fig. 13. The placement of the Tx and the Rx antenna in relation to the room geometry for the short and long-range measurement scenarios is shown in Fig. 14. The spatial-temporal response of the channel is then obtained using the Bartlett beamformer as outlined in [17].

B. Results

In both the short-range and long-range channel measurement a 40 dB dynamic range is considered relative to the power of the LOS component. In the short-range measurement, the power delay profile (PDP) of the channel along the URA...
Fig. 14. Placement of the Tx and the Rx antenna in relation to the room geometry.

Elements is shown in Fig. 15a, where the tail of the PDP is observed to decay at around 100 ns. The sparsity of the channel in the angle and delay domain can be observed in the PADP in Fig. 15b. Besides the four dominant paths that have been identified for this analysis, many weak MPCs exist, which might be crucial to maintaining the radio link when the LOS component or the dominant MPCs are in blockage.

The LOS has an AoA of 269 degrees and a delay of 19.3 ns which corresponds to the Tx and Rx antenna placement and separation distance shown in Fig. 12. The relation of the identified dominant MPCs to the room geometry is shown in Fig. 16. Path 2 and 3 are MPCs originating from the wall with the blackboard in Fig. 12 whereas path 4 is from the curtain behind the Tx antenna. The one to one correspondence of the path trajectory and the identified information in the angle and delay domains indicates a good performance of the channel sounder in a realistic propagation scenario.

The PDP of the measurement campaign in the corridor is shown in Fig. 17. Four dominant MPCs are identified, where the last dominant MPC (path 4) has a delay of 654 ns corresponding to a propagation distance of 196 m. The PADP of the long-range measurement is shown in Fig. 18. The LOS component and path 3 have an AoA of 270 degrees whereas paths 2 and 4 have an AoA of 90 degrees. The mm-wave channel is again observed to be sparse in the angular domain with a few dominant MPCs. Several weak MPCs can also be observed but fade out within 300 ns. It is intuitive to note that two dominant MPCs, path 3 and 4 come after 500 ns. This observation is fundamental in the design of intersymbol interference mitigation mechanisms in radio networks. The relation of the identified MPCs to the room geometry is shown in Fig. 19. Paths 2, 3 and 4 are seen to be first order, second order and third order reflections respectively from the wall behind the Tx and Rx. The identified angle and delay information corresponds well with the path trajectory, an indication of the channel sounder’s performance.

Fig. 15. Short-range indoor channel measurement at a Tx - Rx separation distance is 5.8 m. (a) The PDP with a Hanning window applied to suppress the sidelobes and (b) the PADP. The color bar represents power in dB.

Fig. 16. Relation of the identified MPCs to the room geometry for the short-range channel measurement.
Fig. 17. PDP of the long-range channel measurement with Tx - Rx separation distance of 46 m. A Hanning window is applied to suppress the sidelobes. The color bar represents power in dB.

Fig. 18. PADP of the long-range channel measurement with Tx - Rx separation distance of 46 m. The color bar represents power in dB.

Fig. 19. Relation of the identified MPCs to the room geometry for the long-range channel measurement.
V. CONCLUSION

In this paper, a VNA based channel sounder using RoF techniques has been presented. The channel sounder is validated and specified for the frequency range 1 GHz to 30 GHz for the back to back setup and between 26.5 GHz to 30 GHz for over-the-air measurements due to the limitations imposed by the antennas and the RF amplifier. Using suitable antennas and RF amplifier the channel sounder’s frequency range can be extended to a maximum of 50 GHz. A novel phase compensation mechanism using optical circulators is then shown to maintain the phase deviation from normalization to a maximum of 2.5 degrees at 30 GHz. The amplitude stability is also shown to be robust with a maximum deviation of 0.25 dB over a period of 17 hours. In addition to improvement in the dynamic range to a maximum of 112 dB for the back to back connection at 30 GHz, the long and short-range channel measurements carried out demonstrates the system’s high fidelity.

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