Abstract—This paper presents system concept, calibration and example measurements of a novel ultra-wideband, real-time channel sounder. The sounder operates in the frequency range from 3 GHz to 18 GHz thus providing a Fourier delay resolution of 66.7 ps. The developed sounder measures overlapping sub-bands of 1 GHz bandwidth to cover the whole frequency range. This allows us to use a waveform generator and a digitizer with relatively lower sample rates and significantly lowers the cost compared to sampling the whole band at once. With the transmit power of 40 dBm, the maximum measurable path loss is 132 dB without accounting possible antenna gains. In this work, we also describe the calibration procedure along with the method to patch sub-bands into a combined channel response. This approach is validated by comparing the results from vector network analyzer (VNA) measurements performed in the same static environment. In contrast to VNAs, however, our sounder is real-time and can measure in dynamic environments with maximum Doppler spreads up to 166.7 Hz. Additionally, we present sample results from the first measurement campaign performed in an urban cellular scenario covering 3-18 GHz.

I. INTRODUCTION

As the number of applications and their bandwidth requirements for wireless communications increase, the need for frequency spectrum has also grown [1]. Since the frequencies lower than 6 GHz are mostly occupied, this need can only be met by utilizing the ample spectrum at the higher frequencies that is currently lying fallow. In particular, the emergence of 5G communications has significantly increased interest in mm-wave (millimeter wave) communications [2]. Consequently, there has been a substantial amount of work focusing on the wireless propagation channel measurements in frequency bands higher than 6 GHz [3]. Measurements of mm-wave channels are essential because the propagation characteristics at these short wavelengths are substantially different from the below-6-GHz bands, with diffraction playing a much smaller role, while diffuse scattering is more important. Most of the experimental work focused on bands at 28 GHz, 60 GHz or 75 GHz [3], [4].

However, the transition from microwave into mm-wave frequencies is yet to be studied. Especially the characteristics of the propagation in the frequency range from 10 to 18 GHz are little-known. Most of the measurement campaigns performed in this band focused on a band around 15 GHz [5]. To the best of the author’s knowledge, there is limited work deviating from this trend. [6] provides results for received power and fading statistic for narrowband measurement in Ku band (10-12 GHz) for land mobile satellite channels. [7] investigates delay spread and path-loss for frequency bands, 2.4, 5.2, 10, 17 and 24 GHz with a 250 MHz bandwidth for each band in a laboratory environment. Missing from these measurements is the wideband behavior in the band corresponding to the transition between wavelengths being comparable to the size of many typical objects, to the regime where it is much smaller. Also a host of other papers [8] [9] [10] has compared below-6 GHz with mm-wave propagation, but measuring only a relatively narrow band in each of those frequencies, and thus making it difficult to obtain a physical interpretation of the frequency-dependent effects.

Another important motivation for wideband measurements is the use of UWB (ultra-wide band) communications operating with 500 MHz or more bandwidth, which are allowed to operate from 3.1 GHz to 10.6 GHz in most countries. Large bandwidth and good delay resolution made UWB compelling for applications such as localization, short-range high-speed data transmission, imaging and radar [11]. With this motivation, UWB propagation channel characteristics have been investigated in several different environments; i.e. indoor, outdoor, vehicular [12] [13] [14]. However, no measurements are available in the frequency band above 10 GHz, which is of interest in particular for robust military applications, which are often not subject to FCC emission rules.

We aim to fill these gaps by performing propagation channel measurement over the continuous frequency band from 3 GHz to 18 GHz. As a vital first step, we built a novel time domain channel sounder setup. Even though the instantaneous bandwidth of the setup is only 1 GHz (thus allowing the use of relatively low-cost components), by utilizing a sweeping sub-band approach, it can measure up to 15 GHz total bandwidth in 6 ms. This allows us to measure in dynamic environments as long as the coherence time of the channel is more than 6 ms. At 18 GHz this would correspond to a maximum speed of 5 km/h, which is the typical pedestrian speed [15]. In comparison, a vector network analyzer (VNA), which is the standard choice of equipment for such large bandwidth measurements, would require several hundreds of ms for a similar measurement. The frequency resolution (subcarrier spacing) in our sounder is 500 kHz, corresponding to a maximum measurable excess runlength of multipath components of 600 m (2 μs pseudorange), which is sufficient for all the outdoor environments we consider. Additionally, unlike a VNA, the transmitter (TX) and the receiver (RX) in our setup are physically separated, and they don’t require any cable connections since the synchronization is provided by GPS-stabilized rubidium frequency references. Consequently, the sounder can be used in almost any desired measurement environment. Other than using a VNA, similar measurement can be performed by using high speed arbitrary waveform generators and digitizers [16]. However the cost of such a setup would be significantly higher than the developed
There has been limited work utilizing the sub-band or multi-band measurements. In [17], a similar approach is used to perform measurements at 60 GHz. However, the total measurement time in the proposed setup is 10 s for 5 GHz of total bandwidth so that (contrary to our setup) the sounder in [17] can only be used in static scenarios. Furthermore, the frequency resolution achieved was 8 MHz limiting the maximum measurable delay spread to 37.5 m. Another sounder with the multi-band approach was presented in [18]. This sounder utilizes software defined radios and measures 10 sub-bands of 20 MHz providing a total bandwidth of 200 MHz around 5.6 GHz in 3ms. While this enables measurements in dynamic environments, the bandwidth is almost two orders of magnitude lower than in our device. Furthermore in both the previous works the TX and RX units require a cable connection for sharing reference signal and control signals. Consequently, neither of the setups are suitable for long range measurements as presented in this work.

The contribution of this work thus includes:

- proposing a low-cost time-domain channel sounder setup with a total bandwidth of 15 GHz,
- describing a method for calibration and patching multiple sub-bands into a single frequency response,
- presenting sample results from a first of its kind outdoor measurement campaign performed with the proposed channel sounder.

This paper is organized as follows. Section II describes the details of the sounder setup and its operation principles. Section III discusses the sounder calibration and post-processing of the measurement data. Section IV explains the measurements performed for validation of the sounder operation. Section V provides initial results for a measurement campaign in an urban environment for a cellular scenario. Finally, Section VI concludes the paper with a summary and future work.

II. SYSTEM DESCRIPTION

The proposed setup is a real-time, frequency-hopped multi-band channel sounder with direct up/down conversion. The TX and RX were built as physically separate structures and they don’t require any cabled connection, allowing arbitrary placement of TX and RX. Figures 1 and 2 show the block diagrams for TX and RX respectively. Furthermore, table I lists the part numbers of all the units used in the setup.

A. Single Band Measurements

The TX operation for a single band measurement can be summarized as follows. A 15-bit, 1.25-GSps arbitrary waveform generator (AWG) generates the complex baseband sounding signal. In this measurement campaign, the sounding signal is a multi-tone waveform represented as:

\[ m(t) = \sum_{n=-N}^{N} e^{j(2\pi n \Delta f + \theta_n)} \]  

where \( \Delta f \) is the tone spacing, \( 2N + 1 \) is the number of tones and \( \theta_n \) is the phase of the tone \( n \). As suggested in [19], the values of \( \theta_n \) can be chosen to achieve a low peak to average power ratio (PAPR) signal. In our case the PAPR was 0.4 dB, allowing us to transmit with power as close as possible to the 1 dB compression point of the power amplifier without driving it into saturation. Table II lists further details of the sounding signal. The in-phase and quadrature (I and Q) components of the signal are the real and imaginary parts of \( m(t) \) respectively.

The RX operates in a similar manner to the TX. The
received RF signal is downconverted to baseband I/Q signals and sampled with a 2-channel ADC. The acquired data is written into a RAID array which is equipped with PCIe x4 connection allowing 700 MBps sustained data write speed. Thanks to this, unlike a VNA based sounder, the proposed sounder can operate continuously with a 40% duty cycle. We also note that this is an important difference to the use of a sampling oscilloscope at the RX - while a suitable scope could easily receive the whole 15 GHz bandwidth of interest, it could not provide sustained reading/writing required, e.g., for measuring channel evolution as the mobile station moves on a trajectory.

Both the TX and the RX are controlled with Labview scripts running on National Instruments real-time controllers. GPS-stabilized Rubidium frequency references provide 2 signals for the timing of the setup; a 10 MHz clock to be used as a timebase for all units and 1 PPS (pulse per second) signal aligned to UTC (Universal Time Coordinated). Given the measurement period, hardware counters in the NI DAQ Timing modules are triggered by the 1 PPS signals, and then count the rising edges of the 10 MHz clock and trigger the rest of the units when the counters reach certain values. Since the 1PPS signals in the TX and RX are both aligned to the UTC, they operate synchronously without requiring any physical connections. More importantly, the AWG, the ADC, and the frequency synthesizers were disciplined with the 10 MHz signal provided by these frequency references, hence we are maintaining phase stability during the measurements which is essential for the accurate measurement results [20]. These references also provide GPS locations which are logged along with the measurement data.

B. Multi Band Measurements

All RF units mentioned in Section II-A can operate from 2 GHz to 18 GHz. Additionally, the frequency synthesizers can switch between two arbitrary frequencies within this range in less than 100 µs. Hence they can change the carrier frequency every 100 µs. This is the main feature which allows the construction of the sounder with a frequency sweep approach. One can think the proposed sounder as a hybrid design lying between a VNA and a time-domain sounder setup. Similar to a VNA, it sweeps through different frequency tones to obtain the frequency response of the channel under investigation. However, unlike a VNA using a single tone at a time, it uses a wide-band signal which itself consists of 2001 simultaneously transmitted tones.

Algorithm 1 describes the operation for the multiband measurements, the same procedure runs in TX and RX in parallel. In summary, we perform 30 channel measurements each with 1 GHz bandwidth and carrier frequencies of 3.25 GHz to 17.75 GHz with 500 MHz spacing. Timing modules in TX and RX generate trigger signals with a period of 200 µs. These signals then trigger the synthesizer (to switch to the next carrier frequency) as well as AWG and the ADC. To allow the frequency synthesizers to be stabilized, both the AWG and ADC wait for 120 µs once they received the trigger and then operate for 80 µs, which consists of 20 repetitions of the sounding waveform. This process is repeated for all sub-bands and the acquired data and the metadata (including GPS location, time, ADC gain etc) are transferred into the permanent storage in 1-second chunks.

Algorithm 1 Multi-band Operation: \( N_{m}, N_{bands} \) and \( N_{sweeps} \) are the measurement duration in seconds, number of sub-bands to be measured, and repetition of multi-band measurements per second respectively.

```
1: procedure SWEEP_SOUNDER(\(N_m, N_{bands}, N_{sweeps}\))
2:   \(i \leftarrow 0\)
3:   while \(i < N_m\) do
4:     while 1 PPS trigger not received do
5:       Wait
6:     end while
7:     Start counter for sub-band trigger
8:     for \(k = 0, k++, k < N_{bands} \times N_{sweeps}\) do
9:       \(l \leftarrow k \mod N_{bands}\)
10:      \(s \leftarrow k \div N_{bands}\)
11:     while sub-band trigger not received do
12:       Wait
13:     end while
14:     Wait for 120 \(\mu s\)
15:     Channel sounding for sub-band \(l\) in sweep \(s\)
16:   end for
17:   Store the data
18:   Log GPS location and time
19:   Stop counter
20:   \(i \leftarrow i + 1\)
21: end while
22: end procedure
```
Since the frequency synthesizer is basically a phase locked loop (PLL), every time it switches into a new carrier frequency it introduces a random phase offset relative to the previous carrier. Moreover, the triggering uncertainties of the AWG and ADC add additional phase offsets between TX and RX. These phase offsets can be estimated and corrected if two adjacent sub-bands have overlapping frequency tones. Thus, the frequency plan for the multi-band measurements is designed accordingly as shown in Figure 5. More details about phase correction is given in Section III-B.

Table II summarizes the configuration of the sounder for the measurements presented in this work. The full sweep consists of 30001 tones with 500 kHz spacing over 15 GHz total bandwidth. This configuration provides a time resolution of 66.67 ps with a maximum measurable delay spread of 2 µs. Hence the sounder is capable of distinguishing 2 multi-path components (MPC) if their run-lengths differ by more than 2 cm, and it can measure up to 600 m of maximum run-length for MPCs. However, thanks to the flexible design, almost all the parameters given in the table can be modified according to the goal of the particular channel sounding campaign. Normally the sounder can operate as low as 2 GHz. However, due to interference from WLAN and cellular networks, and licensed spectrum bands we limited our measurements to 3-18 GHz during this campaign. Note that with the addition of band-pass filters, the sounder can also operate like a generic time-domain channel sounder setup with 1 GHz bandwidth and a carrier frequency anywhere between 2 to 18 GHz without any modifications.

III. CALIBRATION

A. Sub-band Estimation

The frequency response of the each sub-band $k$ is estimated with least squares as follows:

$$\hat{H}_k(f_t) = \frac{(H_{m,k}(f_t)/H_{cal,k}(f_t))}{E\{H_{ant,k}(f_t, \theta)\}}$$

(2)

where $H_{m,k}(f)$, $H_{cal,k}(f)$, and $H_{ant,k}(f, \theta)$ are the measured channel response, system response and antenna response for the $k$-th sub-band respectively. The least squares estimation is only performed on the tone frequencies i.e. $f_t \in [f_{LO} - 500MHz, f_{LO} + 500MHz]$, consequently noise enhancement is not an issue. Even though the biconical antennas have a nominally omnidirectional pattern, there are some deviations from that ideal behavior, see Figure 3. Thus, the measured frequency responses of antennas are averaged over all azimuth angles for single-antenna measurements, such as the ones presented here (for directional measurements, obtained, e.g., with an array, the actual directional patterns would be taken into account in the calibration and evaluation).

Since the proposed setup utilizes zero-IF up and down conversion approach, there are two main imperfections of the IQ mixers that needs to be dealt with; LO leakage and IQ phase/amplitude imbalance. For the downconversion mixer (RX side), the LO leakage is filtered out by the low pass filter of the ADC and does not affect the measurements. Conversely in the up-conversion (TX side) if LO power is not properly managed, LO leakage might drive the power amplifier into saturation since the leaked LO will be in the same frequency range with the up-converted RF signal. Consequently, LO power and the power of the baseband sounding signal are adjusted on a per-band basis to ensure that the up-converted RF signal has always more power than the LO leakage and the total power is at least 2 dB less than the input 1dB compression point of the power amplifier. At the RX end, the tones located in $[f_{LO} - 2\Delta f, f_{LO} + 2\Delta f]$ are simply ignored to avoid any misinterpretations due to LO leakage of the IQ mixers.

The imbalances between I and Q channels are measured separately for TX and RX with the method suggested in [21]. For both mixers, the deviation of the relative phase between I and Q channels from 90 degrees, and the mismatch in the amplitudes, were estimated on a per sub-band base. For each sub-band the sounding signal is digitally pre-distorted with the estimated phase and amplitude correction in the TX and for the RX side the acquired data is corrected as described in [22] before further processing. One way to validate the IQ mismatch compensation is checking the sideband suppression ratio with IQ inputs to form a single-sideband modulated signal. Hence for this test, the sounding signal is modified as:

$$m_{USSB}(t) = \sum_{n=-\infty}^{\infty} e^{j 2 \pi f_0 t + \phi_n}$$

(3)
to include only the tones in the upper sideband of the LO. Again the I and Q signals are real and imaginary parts of $m_{\text{USSB}}(t)$. Figure 6 shows the spectrum of the received signal with and without IQ imbalance correction. The sideband suppression ratio, which is the ratio of the power in the desired sideband over to the suppressed sub-band (in this case ratio of the upper sideband over lower sideband) is only 9 dB before the correction for the carrier frequency of 11.75 GHz (the band with the worst IQ imbalance performance initially). The applied IQ imbalance correction increases the sideband suppression ratio to more than 25 dB.

### B. Patching Multiple Bands

In this section we investigate the measurement results for a thru connection to verify the calibration and patching approach. To achieve a comparable SNR in different sub-bands, the power of the sounding signal and the LO is adjusted per sub-band. The same power levels are used in the calibration measurements as well. Figure 7 shows the measured frequency responses (i.e. $H_{m,k}$) for all sub-bands along with the patched frequency response after calibration and IQ imbalance correction. Even though the overlapping tones in the adjacent sub-bands may look different in the initial measurements, once calibrated they are well aligned within 1 dB, and there are no significant discontinuities in the final frequency response. Hence there is no need for additional correction for the amplitude of the frequency response while patching adjacent bands.

In case of the phase response; due to the nature of the PLL in the frequency synthesizer, every time the synthesizer switches to a new carrier frequency, it does so with a random phase. Consequently, there is a random phase offset between consecutive sub-band measurements as seen Figure 8. These offsets change for every run of a full-sweep, hence they need to be estimated and corrected to acquire the true combined phase response for 3 GHz to 18 GHz. The random phase offset from sub-band $k - 1$ to sub-band $k$ is calculated with a maximum likelihood estimator which is formulated as follows:

$$
\theta_k = \begin{cases} 
0, & \text{for } k = 1 \\
\mathcal{L} \left( \sum_{f=0}^{f_s} \hat{H}_{k-1}(f) \hat{H}_k^*(f - f_s) \right), & \text{for } 2 \leq k \leq N
\end{cases}
$$

(4)
where $\angle$ denotes the phase of a complex number and $N$ is the number sub-bands. Finally, the patched complex frequency response for all sub-bands is calculated by;

$$H(f_k + f) = \hat{H}_k(f) \exp \left(i \sum_{n=1}^{k} \theta_n \right)$$

Where: $1 \leq k \leq N_{\text{bands}}$

$-f_s/2 < f \leq f_s/2$

$f_s$ is the step size for the carrier frequencies,

$f_k$ is the $k^{th}$ carrier frequency.

Figure 8 shows the phase response for the uncalibrated sub-band measurements along with the phase response of the full-sweep after performing calibration, IQ imbalance and phase corrections. Additionally, Figure 9 shows the power delay profile (PDP) for a thru connection with and without phase correction. The phase correction removes the undesired ripples caused by phase jumps in the frequency response. To test the temporal stability of the calibration, we repeated the measurement with the thru connection 100 times; the maximum deviation in power was 0.2 dB.

IV. Validation Measurements

As the final verification we compared the results from the channel sounder setup with those from a vector network analyzer (VNA) i.e. measurements of the same wireless channel were taken with the sounder setup and the VNA. For a sample location, figure 10 shows the frequency responses obtained from VNA with the calibrated and patched frequency response acquired with the proposed sounder. Additionally, Figure 11 presents the same comparison for power delay profiles. The same specular components can be observed in both responses, and the power of the LOS path differs only by 0.1 dB between two cases. Consequently, the measurement acquired via the two methods are in good agreement, which validates the proposed sounder and calibration procedure.

V. Measurement Campaign

In this section we present sample results from a measurement campaign performed with the channel sounder. The measurement environment is an urban street as shown in Figure 12. To imitate a cellular scenario, the TX is placed on a roof top at the height of 24 m, while the RX is moved on the ground with an antenna height of 1.8m. 2 different TX locations along with 2 RX routes are selected for LOS (line of sight) and NLOS (none line of sight) measurements. The sounder is configured according to Table II. The LOS measurements were taken on a continuous route on which the TX-RX distance varies from 37 m to 114 m, while the TX-RX distance for NLOS varies from 60 m to 120 m. Figure 13 shows the view from RX facing to the TX for a RX location on the LOS route. Sample PDPs for marked LOS and NLOS locations in Figure 12, are shown in Figure 14. The delays of four specular components observed in the LOS PDP match with the paths shown in Figure 12 with dashed lines. Similarly for the NLOS PDP, the delay of the first path is aligned with the diffracted path while other peaks in PDP are in good agreement with the delays of the possible reflections from surrounding buildings. Moreover, the delays of these path evolve as expected, as the RX moves on its route.

![Fig. 10. Comparison of the measured frequency responses for same environment with VNA and the proposed setup](image1)

![Fig. 11. Comparison of the power delay profiles for same environment with VNA and the proposed setup](image2)

![Fig. 12. Measurement Locations](image3)

![Fig. 13. View from RX for LOS measurements](image4)
Furthermore, Figure 15 shows the PDPs for the same LOS point acquired from single-band measurements at 3 GHz, 10.5 GHz and 18 GHz.

VI. CONCLUSION

In this paper we presented an UWB real-time channel sounder operating from 3 GHz to 18 GHz. Using a frequency-hopped sub-band approach, the sounder can measure the whole band in less than 6ms without requiring high-speed digitizers and waveform generators. Furthermore, we discussed calibration and post-processing steps to combine sub-bands into a single 15 GHz band. Since TX and RX don’t require any physical connection, we were able to perform a first of its kind channel sounding campaign for urban cellular scenario with 15 GHz bandwidth. In future, we will investigate the frequency dependency of the channel parameters for outdoor-cellular and indoor-office environments.

ACKNOWLEDGEMENT

The authors would like to thank DARPA and NSF-MRI (Grant:ECCS-1126732) for their financial support, Northrop Grumman for providing antennas and amplifiers during initial tests.