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Mbugua, Allan Wainaina; Chen, Yun; Fan, Wei

On Simplification of Ray Tracing Channels in Radio Channel Emulators for Device Testing

Allan Wainaina Mbugua*†, Yun Chen*, Wei Fan†,

*Huawei Technologies Duesseldorf GmbH, Munich Research Center, Munich, Germany, allan.mbugua@huawei.com

†Antennas Propagation and Millimetre-Wave Section, Aalborg University, Aalborg, Denmark, wfa@es.aau.dk

Abstract—**Emulation of ray tracing (RT) simulated and measured channels in radio channel emulators is seen as a key enabler for virtual drive testing (VDT). Limitations in emulator hardware resources require that RT simulated or measured channels are simplified. In this preliminary study, the impact of channel simplification is investigated with a target of minimizing the error of the mean delay. The increase in the number of taps in the channel model caused by tap splitting in the conventional constant mean delay method proposed in the literature is addressed by considering the radio frequency (RF) bandwidth of the channel emulator. Although this approach is not optimal, it uses on average 8 taps compared to 24 taps and 36 taps in the original and the tap aligned channels with a constant mean delay, respectively.**

Index Terms—**Channel model simplification, channel emulation, ray tracing.**

I. INTRODUCTION

Radio channel emulators have been adopted in standardization e.g. in 3rd Generation Partnership Project (3GPP) as a core component in the evaluation and performance testing of fourth generation (4G) and fifth generation (5G) devices. This stems from the fact that standard channel models as wells as arbitrary channel models can be replayed in controlled laboratory conditions. Indeed, radio channel emulators have been shown in the literature to facilitate virtual drive testing (VDT) using site-specific channel models generated using ray tracing (RT) simulations [1], [2]. The attractive features of VDT is that it minimizes the need of extensive drive tests in practical deployment scenarios thus reducing costs as well as enabling planning of wireless networks in scenarios where practical channel measurements are not possible.

Generating site-specific channel models using RT for VDT poses some practical challenges on the channel emulation hardware. First for each spatial location, RT tools typically generate hundreds of rays. Second, the rays have arbitrary delay values and finally the channel has infinite bandwidth. On the other hand, although measured channels are band limited owing to the limited bandwidth of practical channel sounders [3], their bandwidth is nonetheless typically greater than that in channel emulators.

Channel emulators have the following properties that inevitably require RT simulated or measured channels to be preprocessed before emulation:

1) Limitation in the number of tap resources which limits the number of multipath component (MPC)s that can be used to represent the channel. For multiple-input multipe-output (MIMO) channel emulation, the number of taps available per channel reduces with increase in the MIMO order since available tap resources are fixed based on the hardware configuration [4].
2) The delay value of the taps can only be in integer values of the sampling time.
3) The finite bandwidth of channel emulators imposes a limit on the achievable delay resolution. Novel band stitching algorithms have been proposed in the literature to increase the available bandwidth by combining several bands, but this comes at a cost of radio frequency (RF) hardware ports as well as digital channels [5].
4) The range of tap amplitudes that can be replayed in the emulator is typically limited e.g. 40 dB in [4].
5) The maximum excess delay that can be emulated on the channel emulator is typically limited by the hardware.
6) The maximum Doppler frequency is also limited by the hardware.

The channel simplification process thus involves reducing the number of taps in the channel model to meet the hardware resources available on the emulator, aligning the delay of the taps to integer multiples of the sampling time and limiting the tap amplitudes to the limit specified by the dynamic range of a specific emulator. The process of generating RT channel models for device testing is illustrated in Fig. 1.
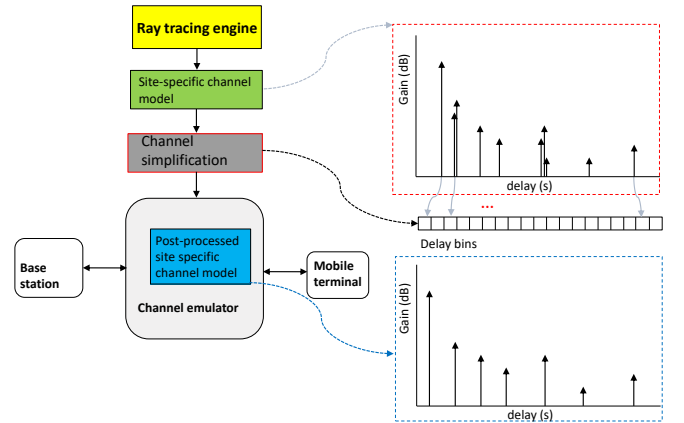

Fig. 1. An illustration of the RT channel generation and simplification process for device testing.

Several methods have been proposed in the literature to simplify measured or RT simulated channel models. In [6],

a linear spline technique was used for pre-processing RT and measured channels whereby adjacent MPCs that fall in one delay bin are vector summed to form a single tap while taking into account correlation of MPCs in a particular bin with MPCs in adjacent delay bins. In [7], three metrics were proposed for removing the least significant paths: a) discarding paths whose power level is below a certain threshold, b) minimizing the delay spread error and c) minimizing the mean square frequency response error. The bit error rate (BER) was observed to be higher when the minimum mean square frequency error criterion was selected. This was attributed to the increase in the delay spread. Indeed, in [8], a similar observation was highlighted where minimizing errors after channel simplification in time and frequency domain could not be maintained simultaneously.

Due to the challenge of preserving multiple channel parameters in the original and simplified channels simultaneously, the channel simplification approaches in the literature aim at preserving specific channel parameters for example the channel frequency response (CFR), the power delay profile, the mean delay, the root mean square (RMS) delay spread or the path loss [9], [10], [8], [11]. The choice of parameter to preserve in turn largely depends on the target application. In time of arrival (ToA) based localization applications, the inaccuracy of the delay information of MPCs has been observed to cause significant ranging and localization errors [12]. Thus in such cases the channel simplification algorithms need not only to align the delays, but also preserve as much as possible the relative delay difference between the MPCs. On the other hand, testing of state-of-the-art algorithms for massive MIMO base stations in emulation set ups requires careful selection of channel parameters to preserve such that the spatial and frequency correlation functions of the channel are not substantially altered compared to the original channel before simplification [13].

In this preliminary study, we explore a method of minimizing the mean delay error $\Delta\bar{\tau}$ in order to save on emulator tap resources. Although, the proposed method saves on tap emulator resources, it is not optimal as it does not address the alteration of the tap amplitudes, and it would additionally be less effective in tap reduction for channel emulators with higher RF bandwidth.

II. SYSTEM MODEL

A. Signal model

Without loss of generality, the time-invariant channel impulse response (CIR) $h_k(\tau, \theta, \phi)$ at the output of a RT for a single-input single-output (SISO) channel with L MPCs at the k-th receiver (Rx) position can be expressed as:

$$h_k(\tau, \theta, \phi) = \sum_{l=1}^{L} E_l \cdot \delta(\tau - \tau_l)\delta(\theta - \theta_l)\delta(\phi - \phi_l)$$

$$E_l = \alpha_l e^{j\psi_l} \cdot g_{Tx}(\theta, \phi)g_{Rx}(\theta, \phi)$$

(1)

where α_l, ψ_l, τ_l, θ_l and ϕ_l are the amplitude, phase, delay, azimuth angle and elevation angle of the l-th MPC, respec-

tively. $\delta(\cdot)$ is the Dirac delta, $g_{Tx}(\theta, \phi)$ and $g_{Rx}(\theta, \phi)$ are the complex radiation patterns of the transmit and receive antennas, respectively. The CIR in (1) would in principle require an infinite bandwidth. In practice, however, due to the finite bandwidth of channel emulators, $\delta(\cdot)$ is replaced by an appropriate filter function $s(\cdot)$ describing the emulator impulse response. Furthermore, the delays of the MPCs τ_l in (1) are arbitrary located thus alignment of the delays of the MPCs to integer multiples of the emulator sampling clock is required.

The constant mean delay algorithm outlined in [9], is employed here to align the tap delays. In this method, when a tap delay τ_l is not an integer multiple of the sampling time T, the tap amplitude is split into two taps; α_l' which is assigned to the delay bin of the adjacent preceding k-th bin and α_l'' is assigned to the adjacent ensuing $(k+1)$-th bin. When the taps coincide the power is summed up to form one tap.

$$\alpha_l'(kT) = \left((k+1) - \frac{\tau_l}{T}\right)\alpha_l$$

$$\alpha_l''((k+1)T) = \left(\frac{\tau_l}{T} - k\right)\alpha_l$$

(2)

Intuitively it can be observed from (2), that in cases where all taps do not fall in integer multiples of the sampling time and none of the split taps falls into the same delay bin, then effectively the number of taps in the channel model is doubled. This is an undesirable situation since in MIMO emulation setups, the number of taps available per logical channel is often limited thus the aligned taps need to be reduced while maintaining a constant mean delay.

To reduce the number of taps that result from the constant mean delay method, we instead consider minimizing the error in the mean delay $\Delta\bar{\tau}$. This is achieved by considering a three stage process:

- Step 1: obtain the CIR with aligned tap delays and with a constant mean delay using (2) [9].
- Step 2: obtain the band-limited CIR of the delay aligned CIR.
- Step 3: obtain the discrete peaks of the band limited CIR and align the delays using (2).

B. Simulation Setup

In the simulation, we consider the emulation of a 100 MHz channel in sub-6 GHz to mimic a 5G cellular system in frequency range 1 (FR1). The channel emulator is modeled with a sampling frequency of 200 MHz hence the CIR taps need to be aligned in integer multiples of the sampling time $T = 5$ ns. For tractability, a synthetic channel with 24 taps with arbitrary tap delays is used to mimic the output of a RT simulation. The number of channel realizations is considered is 1000 CIR per second for 10 seconds resulting in 10000 channel realizations. The synthetic CIR with arbitrary delays is illustrated in Fig. 2 for a single channel realization along with the equivalent band limited CIR.

III. SIMULATION RESULTS

The aligned delays of the synthetic channel are illustrated in Fig. 3 for one channel realization. The number of taps,
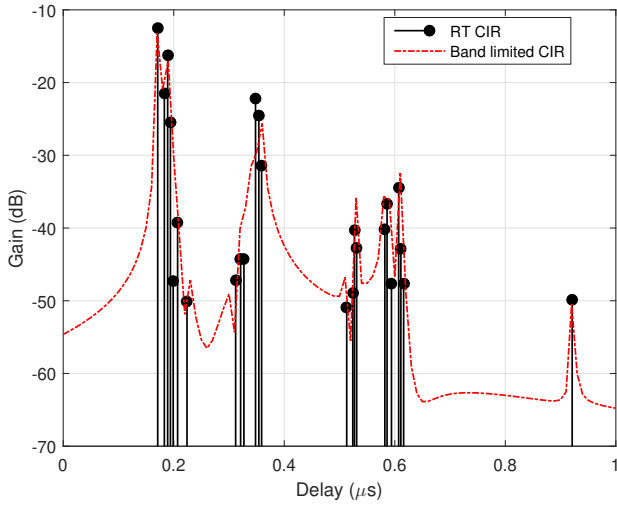
Fig. 2. Synthetic RT simulated CIR with non-aligned tap delays and the equivalent band limited CIR for a single channel realization.

however, are increased from 24 to 36. Furthermore, it can be observed that the relative amplitude of some of the taps is modified which results in a change of the shape of the CIR. Nonetheless, the mean delay is 262 ns which is equal to the original channel shown in Fig. 2. The taps can be reduced by
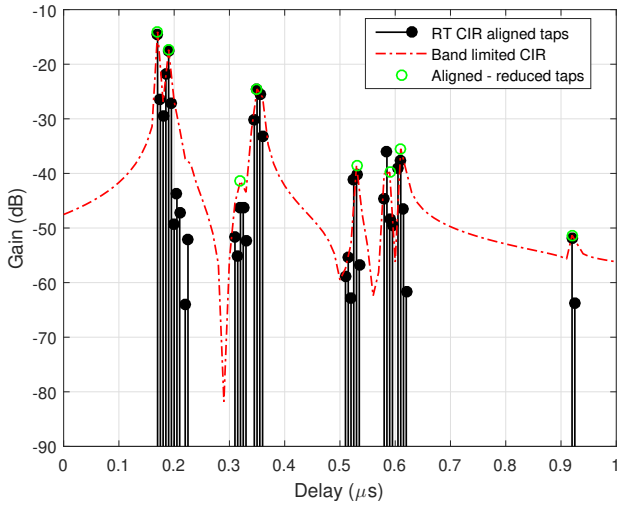

Fig. 3. Synthetic RT simulated CIR with aligned tap delays using the constant mean delay algorithm, the equivalent band limited CIR and the reduced aligned taps for a single channel realization.

considering the band limited CIR of the aligned taps shown in Fig. 3. Since the delay resolution is limited by the RF bandwidth of the emulator, it can be observed that several taps cannot be distinguished in the band limited CIR. However, it is worthwhile to note that since the taps are aligned in delay, they can indeed be replayed in baseband on a digital emulator as long their number, amplitude level and maximum excess delay are within a channel emulator hardware specifications. Besides the higher number of taps obtained compared to the original CIR, the taps obtained also show a significant variation in the

amplitude of over 50 dB. This could potentially be problematic for emulation in practical hardware emulators where the range of tap amplitudes is limited e.g. to 40 dB in [4].

A peak search on the band limited delay aligned CIR is performed to obtain the reduced discrete taps. The discrete taps are then re-aligned using (2). The aligned reduced discrete taps are illustrated in Fig. 3. This yields 8 taps and a mean delay of 243 ns. On the other hand, performing a peak search on the band limited CIR shown in Fig. 2 before the delay alignment and performing a delay alignment on the obtained discrete taps yields a mean delay of 226 ns. A comparison of the band limited original CIR, aligned CIR and aligned CIR with reduced taps is shown in Fig. 4. The adjustment of the delay of the MPCs results in a change of the phase characteristics of the CIR. This could negatively impact precoding techniques in multi-user MIMO test cases where amplitude and phase information is critical for optimal performance of user separation and interference nulling [14].
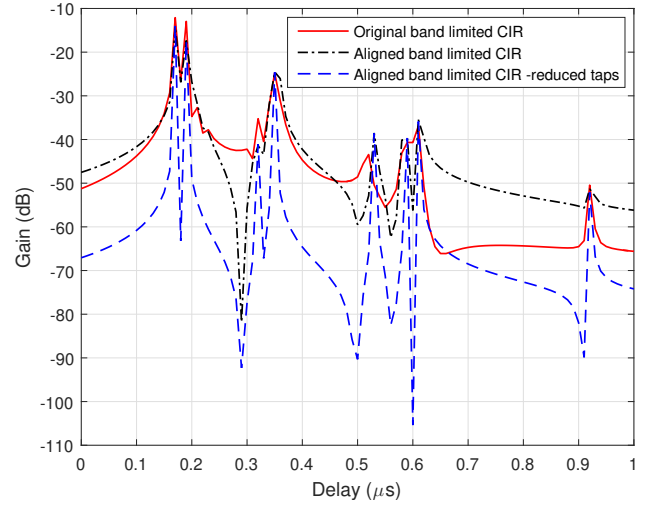

Fig. 4. CIR of the original band limited channel, the aligned band limited channel with a constant mean, and the aligned band limited channel with reduced taps.

To validate the robustness of this technique, 10000 channel realizations with 24 taps each are used in the simulation. Fig. 5 illustrates the mean delay of the original CIR, the band limited CIR with reduced taps after alignment and the band limited CIR with reduced taps before alignment (i.e. skipping step 1). It can be observed that although the mean delay is not maintained by the proposed technique the error $\Delta\bar{\tau}$ is minimized with a mean error of -10 ns a standard deviation (STD) of 14 ns and an root mean square error (RMSE) of 18 ns. Similarly, the RMS delay spread is shown in Fig. 6 and the error in the RMS delay spread $\Delta\bar{\tau}_{rms}$ outlined in Table I. Furthermore, it can be observed that the proposed technique significantly reduces the number of taps by approximately 4 times and 3 times less the number of taps of the aligned CIR with constant mean delay and the original CIR, respectively as shown in Fig. 7.
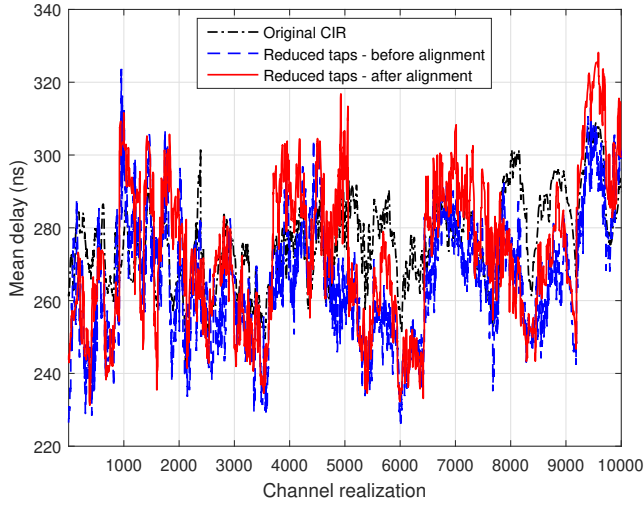
Fig. 5. Mean delay of the original CIR, the reduced taps before alignment and reduced taps after alignment.

TABLE I
STATISTICS OF THE MEAN DELAY ERROR $\Delta\overline{\tau}$ AND THE RMS DELAY SPREAD ERROR $\Delta\overline{\tau}_{rms}$.

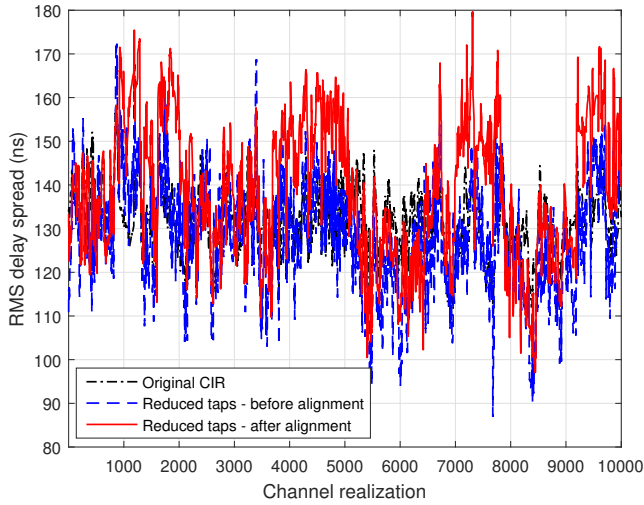| Reduced taps	Mean error (ns)		STD (ns)		RMSE (ns)	
	$\Delta\overline{\tau}$	$\Delta\overline{\tau}_{rms}$	$\Delta\overline{\tau}$	$\Delta\overline{\tau}_{rms}$	$\Delta\overline{\tau}$	$\Delta\overline{\tau}_{rms}$
Before alignment	-3	7	17	14	18	16
After alignment	-10	-3	14	14	18	10

Fig. 6. RMS delay spread of the original CIR, the reduced taps before alignment and reduced taps after alignment.

IV. CONCLUSION

In this preliminary study, the impact of delay alignment of the taps in a synthetic RT simulated CIR are investigated with a target of preserving the mean delay. A common method in the literature used for aligning the tap delays is by splitting a misaligned tap into two; one in the adjacent delay bin immediately below and above the tap with the arbitrary delay. However, this approach causes an increase in the number of
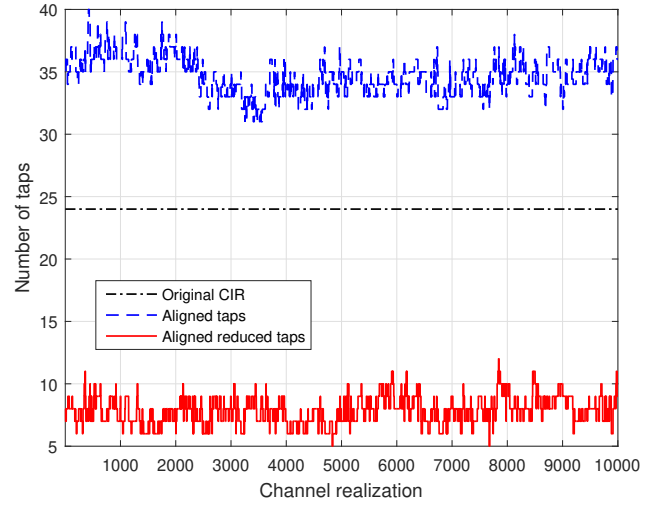

Fig. 7. Number of taps in the original CIR, the aligned CIR with a constant mean and the aligned CIR with reduced taps.

taps which might not be feasible for emulation of MIMO channels. Tap reduction is proposed by considering the RF bandwidth of the emulator. Although the mean delay of the CIR with reduced taps is not maintained, the error $\Delta\overline{\tau}$ is kept reasonably minimal. This technique significantly reduces the number of taps, where for the synthetic CIR considered, approximately 3 and 4 times tap reduction is achieved in comparison to the original CIR and aligned CIR, respectively. Furthermore, the variation of the tap amplitude is intuitively reduced by the proposed method which is a critical parameter considering the dynamic range of practical channel emulators. However, this strategy of tap reduction is not optimal due to the modification of the original tap amplitude and delay properties. Moreover, for channel emulators with higher RF bandwidth, the delay resolution increases resulting in a lower capability of this strategy to reduce the number of taps. Future work will aim at looking at optimal techniques of preserving the channel characteristics.

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