Interference due to Phase Noise in Downlink Multi-TRP Scenario

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***Abstract*—Sub-terahertz band is significantly influenced by phase noise, making phase noise compensation essential for sub-terahertz communication systems. Compensating intercarrier interference (ICI) due to phase noise typically utilizes the reference signals and data from neighboring subcarriers, so the resources utilized for phase noise estimation are required to have similar interference environment to reliably estimate the phase noise. In this paper, we employ a system model to investigate the effect of the ICI due to phase noise at the receiver side of an orthogonal frequency division multiplexing (OFDM) system in a downlink multi-transmitter/receiver (TRP) environment. We explore resource mapping strategies to ensure that the resources utilized for phase noise estimation share similar interference environment. This paper also includes evaluations of the resource mappings we have considered.**

***Keywords*—multi-TRP, phase noise**

I. INTRODUCTION

One of the most significant impairments in sub-terahertz communication systems is phase noise which is due to a time-varying phase drift of the local oscillator (LO). Phase noise grows quadratically with the carrier frequency [1] and the process of estimating and compensating for phase noise is one of the factors that determine the performance of the sub-terahertz communication systems.

In orthogonal frequency division multiplexing (OFDM) systems, phase noise is typically estimated and compensated in the frequency domain. This phase noise can be categorized into two components: common phase noise (CPE) and intercarrier interference (ICI). CPE is a common distortion which affects all subcarriers uniformly, while ICI is the interference between adjacent subcarriers [1].

OFDM systems estimate the phase noise spectrum using reference signal (RS) to mitigate these distortions caused by phase noise [2]. To enhance the reliability of the phase noise spectrum estimation, channel estimation error should be minimized and the resources utilized for phase noise estimation should share similar interference environment. However multi-antenna or multi-transmitter/receiver point (TRP) environments, the interference environment of RS and adjacent subcarrier signals used for phase noise estimation may vary depending on RS mapping, and the resulting degradation in the reliability of the phase noise spectrum estimation may lead to a degradation in the overall system performance.

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In this paper, we focus on the impact of interference caused by relatively wide band phase noise compared to subcarrier spacing of OFDM systems in downlink multi-TRP scenario. We also propose resource mapping plans including phase noise estimation RSs and briefly discuss about the evaluation of each mapping plan.

II. PHASE NOISE IN SYSTEM MODELS

A. Downlink Multi-TRP System Model

In this paper, we consider a scenario where two TRPs each with a single antenna transmit Cyclic Prefix-Orthogonal Frequency Division Multiplexing (CP-OFDM) signals to a terminal with two antennas, as shown in Fig. 1.

In CP-OFDM, the information bits are QAM modulated and mapped in frequency-time domain. Let $\mathbf{x}_A$ and $\mathbf{x}_B$ denote the transmitted frequency domain length N symbol vectors each from TRP A and TRP B, respectively. At the terminal side, the received frequency domain symbol vector can be given by

$$\mathbf{y} = \begin{bmatrix}\mathbf{y}_1\\ \mathbf{y}_2\end{bmatrix} = \begin{bmatrix}\mathbf{P}_R & \mathbf{0}_N\\ \mathbf{0}_N & \mathbf{P}_R\end{bmatrix}\begin{bmatrix}\mathbf{H}_{(1,A)} & \mathbf{H}_{(1,B)}\\ \mathbf{H}_{(2,A)} & \mathbf{H}_{(2,B)}\end{bmatrix}\begin{bmatrix}\mathbf{P}_A & \mathbf{0}_N\\ \mathbf{0}_N & \mathbf{P}_B\end{bmatrix}\begin{bmatrix}\mathbf{x}_A\\ \mathbf{x}_B\end{bmatrix}, \quad (1)$$

where $\mathbf{y}_1$ and $\mathbf{y}_2$ are the frequency domain received CP-OFDM symbol at the terminal with the 1st antenna and the 2nd antenna, respectively, and $\mathbf{H}_{(n,TRP)}$ is the $N \times N$ channel matrix between TRP and the n-th antenna of the terminal. $\mathbf{P}_A$ and $\mathbf{P}_B$ are the $N \times N$ phase noise matrices of TRP A and TRP B, respectively, and $\mathbf{P}_R$ is also the $N \times N$ phase noise matrix which is common across the receiving antennas of the terminal. We assumed that the mobility of the terminal is very low and the channel coherence time is relatively large compared to the CP-OFDM symbol duration. In this case, the channel matrix $\mathbf{H}_{(n,TRP)}$ can be considered as a diagonal matrix.

Channel can be estimated from the received symbol containing channel estimation RS, such as DM-RS in 5G NR. The estimated channel can be used to equalize the channel fading for several subsequent data symbols since the channel is assumed to be slow-varying, and therefore the symbols containing channel estimation RSs can be sparsely positioned in time. The effective channel estimated at the symbol $\mathbf{y}^{CH}$ which is carrying channel estimation RS is expressed as

$$\widehat{\mathbf{H}} = \begin{bmatrix}\mathbf{P}_R^{CH} & \mathbf{0}_N\\ \mathbf{0}_N & \mathbf{P}_R^{CH}\end{bmatrix}\begin{bmatrix}\mathbf{H}_{(1,A)} & \mathbf{H}_{(1,B)}\\ \mathbf{H}_{(2,A)} & \mathbf{H}_{(2,B)}\end{bmatrix}\begin{bmatrix}\mathbf{P}_A^{CH} & \mathbf{0}_N\\ \mathbf{0}_N & \mathbf{P}_B^{CH}\end{bmatrix}, \quad (2)$$

where $\mathbf{P}_R^{CH}$, $\mathbf{P}_A^{CH}$ and $\mathbf{P}_B^{CH}$ are the instantaneous phase noise matrices at the symbol $\mathbf{y}^{CH}$. We assume that the channel

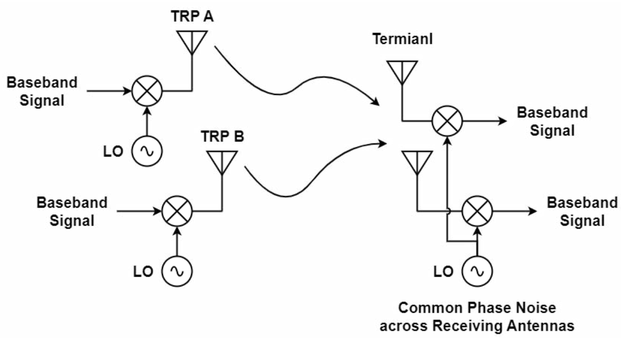


Fig. 1. Downlink multi-TRP scenario

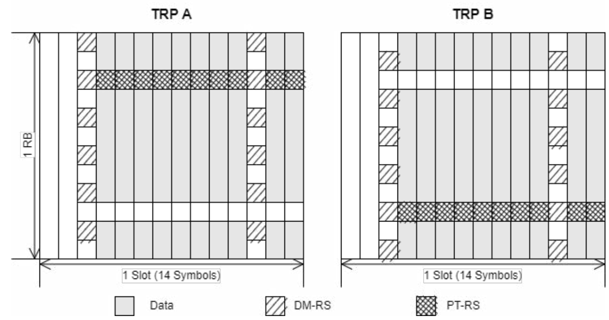


Fig. 2. Conventional resource mapping for downlink multi-TRP scenario

remains constant as long as we continue to utilize the channel information which is obtained from the preceding RS. Then at the receiver, the frequency domain received symbol vector $\mathbf{y}$ is equalized with the estimated effective channel matrix as

$$\hat{\mathbf{x}} = \left(\widehat{\mathbf{H}}\right)^{-1}\mathbf{y} = \begin{bmatrix} (\mathbf{Q}_A^{CH})^{\mathrm{T}} & \mathbf{0}_N \\ \mathbf{0}_N & (\mathbf{Q}_B^{CH})^{\mathrm{T}} \end{bmatrix} \mathbf{V} \begin{bmatrix} \mathbf{P}_A & \mathbf{0}_N \\ \mathbf{0}_N & \mathbf{P}_B \end{bmatrix} \begin{bmatrix} \mathbf{x}_A \\ \mathbf{x}_B \end{bmatrix}, \quad (3)$$

where $(\mathbf{Q}_{TRP}^{CH})^{\mathrm{T}} = (\mathbf{P}_{TRP}^{CH})^{-1}$ and $\mathbf{V}$ is a matrix formed by the multiplication of channel matrices and residual phase noise matrix, given by

$$\mathbf{V} = \begin{bmatrix} \mathbf{V}_{11} & \mathbf{V}_{12} \\ \mathbf{V}_{21} & \mathbf{V}_{22} \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{H}_{(1,A)} & \mathbf{H}_{(1,B)} \\ \mathbf{H}_{(2,A)} & \mathbf{H}_{(2,B)} \end{bmatrix}^{-1} \begin{bmatrix} \widetilde{\mathbf{P}}_R & \mathbf{0}_N \\ \mathbf{0}_N & \widetilde{\mathbf{P}}_R \end{bmatrix} \begin{bmatrix} \mathbf{H}_{(1,A)} & \mathbf{H}_{(1,B)} \\ \mathbf{H}_{(2,A)} & \mathbf{H}_{(2,B)} \end{bmatrix}, \quad (4)$$

where the residual phase noise matrix $\widetilde{\mathbf{P}}_R = (\mathbf{P}_R^{CH})^{-1}\mathbf{P}_R$ and can be considered as a circulant matrix. To observe the inter-TRP interference of phase noise, $\hat{\mathbf{x}}_A$ which is transmitted from TRP A can be estimated from $\hat{\mathbf{x}}$, as

$$\hat{\mathbf{x}}_A = \underbrace{(\mathbf{Q}_A^{CH})^{\mathrm{T}}\mathbf{V}_{11}\mathbf{P}_A\mathbf{x}_A}_{\substack{intra-TRP \\ interference}} + \underbrace{(\mathbf{Q}_A^{CH})^{\mathrm{T}}\mathbf{V}_{12}\mathbf{P}_B\mathbf{x}_B}_{\substack{inter-TRP \\ interference}}, \quad (5)$$

$\hat{\mathbf{x}}_A$, transmitted vector from TRP A, can be separated into intra-TRP interference component and inter-TRP interference component. Intra-TRP interference refers to the interference that is originated from within TRP A and Inter-TRP interference refers to the interference from TRP B. To observe the interference from adjacent subcarriers, the estimated n-th subcarrier signal $\hat{x}_{A,n}$ can be extracted from $\hat{\mathbf{x}}_A$, as

$$\hat{x}_{A,n} = \left(\hat{x}_{A,n}\Big|_{\substack{intra-TRP \\ intra-carrier}} + \hat{x}_{A,n}\Big|_{\substack{intra-TRP \\ inter-carrier}} \right) + \left(\hat{x}_{A,n}\Big|_{\substack{inter-TRP \\ intra-carrier}} + \hat{x}_{A,n}\Big|_{\substack{inter-TRP \\ inter-carrier}} \right). \quad (6)$$

where each of the elements in (6) can be calculated as

$$\hat{x}_{A,n}\Big|_{\substack{intra-TRP \\ intra-carrier}} = x_{A,n} \sum_{u=-U}^{U} \left\{ p_{A,u} \sum_{\substack{v=\max \\ (-U,-u-U)}}^{\substack{\min \\ (U,-u+U)}} f(u,v) \right\} \quad (7)$$

$$\hat{x}_{A,n}\Big|_{\substack{intra-TRP \\ inter-carrier}} = \sum_{\substack{k=-n \\ k\neq 0}}^{N-n-1} \left\{ x_{A,n+k} \sum_{u=-U}^{U} \left\{ p_{A,u} \sum_{\substack{v=\max \\ (-U,k-u-U)}}^{\substack{\min \\ (U,k-u+U)}} f(u,v) \right\} \right\} \quad (8)$$

$$\hat{x}_{A,n}\Big|_{\substack{inter-TRP \\ intra-carrier}} = x_{B,n} \sum_{u=-U}^{U} \left\{ p_{A,u} \sum_{\substack{v=\max \\ (-U,-u-U)}}^{\substack{\min \\ (U,-u+U)}} f(u,v) \right\} \quad (9)$$

$$\hat{x}_{A,n}\Big|_{\substack{inter-TRP \\ inter-carrier}} = \sum_{\substack{k=-n \\ k\neq 0}}^{N-n-1} \left\{ x_{B,n+k} \sum_{u=-U}^{U} \left\{ p_{A,u} \sum_{\substack{v=max \\ (-U,k-u-U)}}^{\substack{min \\ (U,k-u+U)}} f(u,v) \right\} \right\} \quad (10)$$

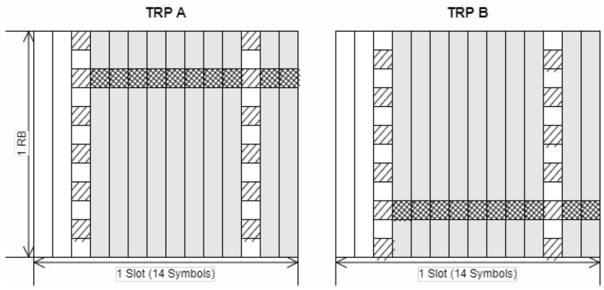
where $f(u,v)$ is the function of residual phase noise matrix elements and channel fading matrix elements. When $U = 0$, the value of the function, $f(0,0)$, equals one. If the subcarrier spacing is sufficiently wide to eliminate the impact of interference, U can be set to 0 and (6) can be simplified as

$$\hat{x}_{A,n} = x_{A,n}p_{A,0}q_{A,0}^{CH}\tilde{p}_{R,0}, \quad (11)$$

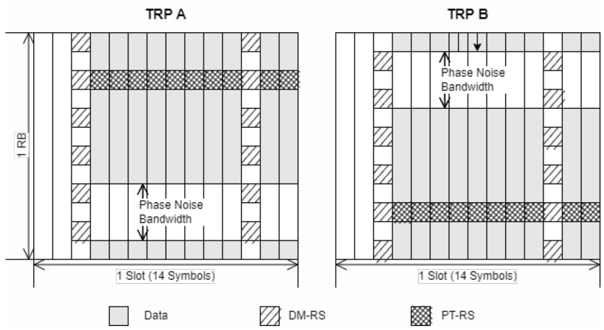
where $p_{A,0}$, $q_{A,0}^{CH}$ and $\tilde{p}_{R,0}$ are diagonal elements of $\mathbf{P}_A$, $\mathbf{Q}_A^{CH}$ and $\widetilde{\mathbf{P}}_R$, respectively. As shown in (11), if the effective bandwidth of the phase noise is narrower than the subcarrier spacing, both the interference between the TRPs and ICI within the TRP will vanish, resulting in the same value as the single TRP scenario.

B. Phase Noise Estimation in Downlink Multi-TRP Scenario

One of widely used approach to estimate the phase noise spectrum and to compensate phase noise is to use de-ICI filter at the receiver [3]. The coefficients of de-ICI filter are typically calculated by phase tracking RS (PT-RS) along with



(a) Mapping A



(b) Mapping B

Fig. 4. Examples of RS mapping for downlink multi-TRP scenario

neighboring subcarriers. Assume that the channel-equalized received signal is represented as

$$R_k^{eq} = \sum_{n=0}^{N-1} (X_n J_{k-n}), \tag{12}$$

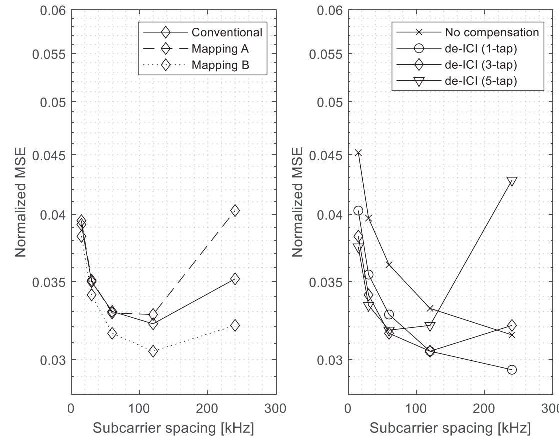
where $\{X_{n+u} | -2U \leq u \leq 2U\}$ and $\{R_{n-u}^{eq} | -U \leq u \leq U\}$ are PT-RS and channel-equalized received signal, respectively, and $\{J_u | -U \leq u \leq U\}$ is the frequency response of phase noise to estimate. Then, de-ICI filter can be designed at the receiver as

$$\sum_{m=-U}^{U} \left(a_m R_{k-m}^{eq}\right) \approx X_k, \text{for } k \in \{k_0, k_1, \cdots, k_{K-1}\}, \tag{13}$$

where a_m is the m-th coefficient of de-ICI filter with $2U+1$ taps and can be calculated as

$$\begin{aligned} &\hat{a}_{-u}, \cdots, \hat{a}_u \\ &= \underset{a_{-u},\cdots,a_u}{arg\ min} \left\| \begin{bmatrix} R_{k_0+U}^{eq} & \cdots & R_{k_0-U}^{eq} \\ \vdots & \ddots & \vdots \\ R_{k_{K-1}+U}^{eq} & \cdots & R_{k_{K-1}-U}^{eq} \end{bmatrix} \begin{bmatrix} a_{-u} \\ \vdots \\ a_u \end{bmatrix} \right. \\ &\left. - \begin{bmatrix} X_{k_0} \\ \vdots \\ X_{k_{K-1}} \end{bmatrix} \right\|^2 = \arg\min_{\mathbf{A}} \left\| \mathbf{R}_u^{eq} \mathbf{A} - \mathbf{X} \right\|^2 \end{aligned} \tag{14}$$

$$\widehat{\mathbf{A}} = \left(\left(\mathbf{R}_u^{eq}\right)^{\mathrm{H}} \mathbf{R}_u^{eq} \right)^{-1} \left(\mathbf{R}_u^{eq}\right)^{\mathrm{H}} \mathbf{X}. \tag{15}$$



(a) 3-Tap de-ICI Filter (b) Mapping B

Fig. 3. Evaluation on RS Mapping Strategies

As shown in (15), to enhance the reliability of estimating and compensating phase noise using de-ICI filter, channel estimation error should be minimized and PT-RS and neighboring subcarriers utilized for phase noise estimation should share same interference environment. Considering conventional resource mapping in Fig. 2, the estimation of received subcarriers adjacent to PT-RS can be expressed as (6) but the estimation of received PT-RS itself has a different form, as shown below.

$$\begin{aligned} \hat{x}_{A,n}^{PTRS} = &\left(\hat{x}_{A,n}^{PTRS}\Big|_{\substack{intra-TRP \\ intra-carrier}} + \hat{x}_{A,n}^{PTRS}\Big|_{\substack{intra-TRP \\ inter-carrier}} \right) \\ &+ \hat{x}_{A,n}^{PTRS}\Big|_{\substack{inter-TRP \\ inter-carrier}}. \end{aligned} \tag{16}$$

III. Resource Mapping for Phase Noise Estimation

As seen in (6) and (16), the resources utilized for phase noise estimation do not experience the same interference environment depending on the resource mapping. To address this, a new resource mapping, such as in Fig. 3, can be employed.

Fig. 3(a) shows an example of resource mapping where all TRPs do not block the resources which other TRPs allocate to PT-RSs. In this scenario, all the resources utilized for phase noise estimation go through similar interference environment, all experience ICI and inter-TRP interference. In contrast, Fig. 3(b) presents an example of resource mapping where all TRPs block both the subcarriers assigned to PT-RSs by other TRPs and their neighboring subcarriers. Here, all the resource utilized for phase noise estimation remain free from inter-TRP interference.

IV. Simulations

Fig. 4 illustrates the normalized mean symbol error (NMSE) performance of the OFDM system, following the resource mapping introduced in Fig. 3. In the simulation, TDL-E channel model with 22 dB of K-factor is employed and the delay spread is set to 10 ns. The bandwidth and TTI length of the simulation system is 100 MHz and 0.25 ms, respectively. The phase noise model employed in this simulation is sub-terahertz phase noise model which is developed by 3GPP based on the published documents and inputs from hardware manufacturers [5].

In Fig. 4(a), NMSE performance difference can be observed according to the resource mappings. However, contrary to our expectation, the resource mapping strategy does not show significant NMSE performance improvement under narrow subcarrier spacing numerologies in which the phase noise spectrum bandwidth exceeds the subcarrier spacing. And for the wider subcarrier spacing, all the resource mappings including mapping A and B show performance degradation when compared to the case under numerologies with narrow subcarrier spacings. The MMSE performances of two resource mappings are similarly degraded as the subcarrier spacing gets wider but the causes of the degradation are different for two mappings.

PT-RS in mapping A may be vulnerable to ICI introduced by varying channel and PT-RS may interpret ICI caused by the channel as ICI due to phase noise spectrum, particularly in a condition where the impairment from channel estimation error or the interference due to fast fading channel dominates over the ICI by the phase noise, such as in a fast fading channel under numerologies with wide subcarrier spacing, leading to inaccuracy in phase noise estimation. This inaccuracy gets worse for a receiver with large number of de-ICI taps which is ready to estimate wide range of ICI interference due to phase noise. Consequently, utilizing this erroneously estimated phase noise for compensation may result in performance degradation in wide subcarrier spacing scenarios. PT-RS in this mapping is also susceptible to inter-TRP interference, which further diminishes the phase noise estimation reliability. For mapping B, PT-RS is designed to mitigate both inter-TRP interference and contamination due to ICI. The resources for phase noise estimation in this mapping are under a low interference environment, and the phase noise matrix generated by large group PTRS is likely to be more ill-conditioned compared to the phase noise matrix in other mapping scenarios.

Fig. 4(b) clearly shows that using the de-ICI filter bandwidth that exceeds the actual phase noise bandwidth causes performance degradation. Fig. 4(b) also shows that increasing subcarrier spacing in all resource mappings enhances NMSE performance for a receiver equipped solely with CPE correction, without any additional ICI compensation.

V. Conclusion

In this paper, we have investigated how the phase noise is represented in a downlink multi-TRP environment when the frequency bandwidth of the phase noise spectrum exceeds the subcarrier spacing, i.e., when phase noise causes ICI in OFDM systems. Furthermore, we have introduced new resource mapping strategies which are suitable for a downlink multi-TRP environment and evaluated their performance through simulation.

However, the simulation results show that optimizing the bandwidth of the phase noise compensation filter is more effective to improve NMSE performance compare to using resource mappings to create a similar interference environment across the resources used for phase noise estimation. Further simulations covering various resource mappings and numerologies are considered to be required for more comprehensive understanding of the representation of phase noise in downlink multi-TRP scenario and the evaluation results.

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