

Boundary on Channel Reconstruction Accuracy of RePH

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Over-the-air testing of human-sensing radar is problematic because it involves human subjects, resulting in increased testing costs and unfair benchmarking due to the non-reproducibility of the subject's vital signs. As an alternative to human subjects, we propose a reconfigurable electronic phantom (RePH) using a reconfigurable intelligent surface. RePH consists of array antennas and variable loads connected to each array element. By varying the load reflection coefficients, RePH passively reconstructs the radar channel, including the influences of the subject's vital signs. Larger array aperture and more spatial degrees of freedom (DoF) of RePH can improve the reconstruction accuracy; however, mismatches and mutual couplings of the array elements diminish it. Thus, in this paper, we elucidate the channel reconstruction boundary of RePH achieved by compensating for the intra-array mismatches and mutual couplings.

Fig. 1 shows a conceptual diagram of RePH. The reconstructed channel $\mathbf{H}_{\text{RePH}}$ is expressed using channel matrices as shown in Fig. 1. $\mathbf{S}_{\text{PP}}$ is an S-matrix representing the reflections and mutual couplings of the RePH's array elements, and $\mathbf{\Gamma}$ is a diagonal matrix with reflection coefficients of variable loads. The target channel can be approximately reconstructed by optimizing $\mathbf{\Gamma}$ so that $\|\mathbf{H} - \mathbf{H}_{\text{RePH}}\|_{\text{F}}$ is minimized, assuming the impact of $\mathbf{S}_{\text{PP}}$ is minor. In practice, however, $\mathbf{S}_{\text{PP}}$ is non-negligible and causes reconstruction errors. Therefore, we discuss the reconstruction accuracy achieved by compensating for $\mathbf{S}_{\text{PP}}$ using a multiport conjugate matching network (MCMN) (J. W. Wallace et al., IEEE Trans. Wirel. Commun., Jul. 2004.). Fig. 2 shows a conceptual diagram of RePH using MCMN. The MCMN consists of decoupling, matching, and transmission parts, and the last can be expressed as an arbitrary unitary transformation $\mathbf{U}$. By connecting the MCMN to the RePH, the effect of $\mathbf{S}_{\text{PP}}$ can be eliminated from $\mathbf{H}_{\text{RePH}}$. Finally, by jointly optimizing $\mathbf{U}$ and $\mathbf{\Gamma}$, the channel reconstruction boundary of RePH can be investigated.

To analyze the reconstruction boundary of RePH, we conducted a full-wave simulation. The analysis frequency was 2.47125 GHz. A radar's transmitter (Tx) and receiver (Rx) each consisted of a half-wavelength-spaced 2-element linear patch array. The Tx and Rx were vertically separated by one wavelength. RePH consisted of a half-wavelength-spaced N -element square patch array placed 1.0 m in front of the radar. A perfect conductor cylinder of 0.2 m height and 0.1 m radius was used as the target. RePH reconstructed the radar channel when the target was at a distance r in front of the radar. Fig. 3 shows the channel reconstruction error ε by RePH with MCMN versus the distance r and the number of antennas N . The star markers in Fig. 3 indicate the minimum distance for each N at which the reconstructed and target channels coincide, i.e., the reconstruction boundary. The white line shows the theoretical formula for r and N satisfying the condition the channel gain based on the geometric channel model is equivalent to that of the target channel. In particular, for small N , the reconstruction boundary does not agree with the theoretical formula. The results suggest that the channel reconstruction boundary of RePH is determined by not only the channel gain, i.e., array aperture, but also the channel controllability by spatial DoF.

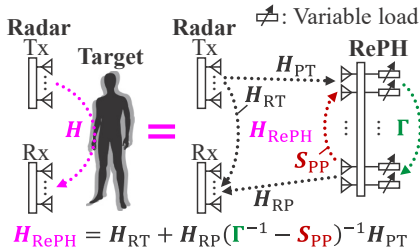


Fig. 1. Concept of RePH.

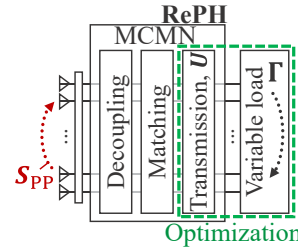


Fig. 2. RePH with MCMN.

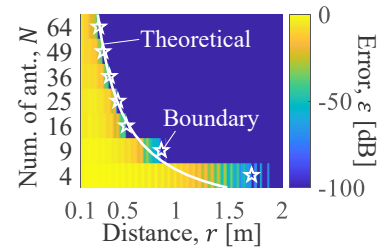


Fig. 3. Reconstruction error of RePH with MCMN.