

The Near Field Effect in Transmitter Design for Incoherent Millimeter-Wave Imaging

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Abstract

The use of incoherent signal illumination is seeing increasing interest for millimeter-wave imaging applications, due to the fact that the transmitters and receivers need not be synchronized in such systems. Furthermore, exact knowledge of the transmit waveforms and the resultant radiation pattern is not required either, so long as the spatio-temporal radiation pattern is sufficiently uncorrelated. Designing the transmit systems to ensure such spatio-temporal properties is not always straight-forward, especially when a small number of transmitters is used, since the image plane is typically in the near-field of the array. In this paper, we discuss the connection between the near field and spatio-temporal incoherence for illuminating signals in incoherent millimeter-wave imaging.

1 Introduction

Space-time incoherent fields are widely used in applications using optical frequencies [1], however at microwave and millimeter-wave frequencies, such signals are not commonly utilized, as most systems coherently process transmit and receive signals. For example, radar systems perform coherent processing of the received signals compared to the transmit waveform properties, and phased array antennas require element-to-element coherence between both transmit and receive elements [2]. Interferometric imaging uses sparse antenna arrays that capture the field from incoherent sources. Applications include radio astronomy [3] and passive millimeter-wave imaging of humans [4, 5]. These applications utilize thermal radiation which satisfies the Van Cittert-Zernike theorem requirements [1] which dictate that the fields should be incoherent in both space and time. However, thermal radiation is extremely low power at millimeter-wave frequencies and this leads to high system cost due to very high sensitivity and wide bandwidth receivers needed [6–8]. These requirements are significantly relaxed in active coherent systems like radar since the transmit power yields a strong reflected signal.

The newly introduced technique called active incoherent millimeter-wave imaging uses noise transmission from multiple locations in order to mimic the properties of thermal radiation and achieve spatial incoherence [9, 10]. The use of active transmission of the noise signals results in a significant relaxation of the sensitivity and bandwidth re-

quirements in passive imagers, thereby enabling image formation with commercial receiver hardware. It is furthermore possible to capture signals of interest radiated from non-cooperative sources, provided that they are sufficiently incoherent across space and time [11]. Many advantages come with this newly introduced approach including the use of very sparse antenna arrays resulting in less hardware than phased arrays [12], minimal knowledge requirements of the transmit signals, no requirements for transmitter-receiver synchronization, and the use of fast Fourier processing. Using the far field radiation of N noise transmitters, partial spatial coherence of $1/N$ at the worst case is obtained [13]. However, it is not always possible to have a large number of incoherent transmitters, which makes it important to examine different techniques to achieve spatial incoherence. In this work we examine the use of near field illumination from an array of noise transmitters. We first introduce the theory and then we include simulations of near field incoherent signal transmission.

2 Near Field Noise Illumination and Incoherence

Consider two millimeter-wave incoherent noise transmitters residing on the $x - y$ plane, where the i^{th} transmitter resides at $(x_i, 0)$. For the interferometric image reconstruction to succeed each spatial point response needs to be statistically independent from the other. The two independent noise sources are illuminating the scene with incoherent signals, however their superposition might not be necessarily spatially incoherent, as it can also be seen from the Fig. 1. The two targets get different contributions of the incoherent signals when illuminated from near field radiation (top), Fresnel zone (middle), and far field illumination (bottom). This can be seen also from the phase wavefronts at the bottom of Fig. 1. The two targets get almost the same contribution of the phase wavefronts with colors green and yellow in the bottom. This is not the case for the near field example at the top of Fig. 1, where the circular wavefronts can give very different contribution on the targets. The metric we use in this study to evaluate how much the phase of the electric field E at one point i is different from another point j is the mutual coherence matrix γ . Each matrix element γ_{ij} is the dot product of the spatial point responses ϵ_i and ϵ_j as a function of time and can be written as

$$\gamma_{ij} = \frac{|\epsilon_i \epsilon_j^H|}{\|\epsilon_i\| \cdot \|\epsilon_j\|} \quad (1)$$

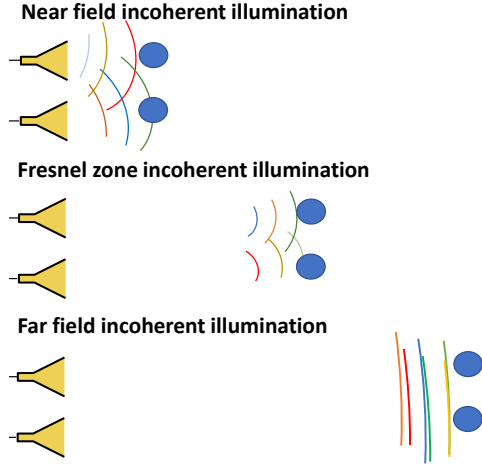


Figure 1. Comparison between near field (top), Fresnel zone (middle), and far field (bottom) incoherent illuminations. Near field radiation gives the most diverse contributions to the two targets as it can be seen from the superposition of the phase wavefronts. Fresnel zone illumination gives a little less diverse contributions and the two targets on the bottom receive almost the same contribution from the approximately planar green and yellow lines in the far field.

where $\|\cdot\|$ is the l_2 norm. When γ_{ij} is close to 1, the spatial points i, j are coherent, while when γ_{ij} is close to 0 the points i, j are incoherent [13]. In a 2-D space (x, y) the field from N transmitters at a carrier frequency f_c with bandwidth Δf as a function of time can be given as

$$E(x, y, t) = \sum_{i=1}^N \int_{f_c - \frac{\Delta f}{2}}^{f_c + \frac{\Delta f}{2}} s_{N_i}(t) * \frac{\delta(t - R_i/c)}{R_i} df \quad (2)$$

where $*$ corresponds to convolution, $s_{N_i}(t)$ is the noise signal from the i -th transmitter, and $R_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$ is the distance of each point (x, y) from the transmitters locations (x_i, y_i) .

The results of the mutual coherence at a 1-D image plane can be seen in Fig. 2(a)-(c) for $N=2$ 38 GHz noise transmitters. All the results correspond to the scene being at a distance of 5 m away from the noise sources and the spatial mutual coherence was calculated along a line of 2 m. The transmitter separation was changed to simulate the far field, Fresnel zone, and near field. The results in Fig. 2(a) are from a transmit separation of 20 cm which corresponds to far field and it can be seen from the main diagonal that every point is self coherent with itself as expected. However, the anti-diagonal lines with amplitude close to 1/2 show that almost every spatial point has another point that is partial coherent with it, which is unwanted coherence. Increasing the transmitter separation to 1.6 m pushes the unwanted partial coherence lines to the edges of the field of view as it can be seen in Fig. 2(b) for Fresnel region radiation. Finally, increasing the transmit separation to 2.8 m completely eliminates the partial coherence lines inside the field of view as

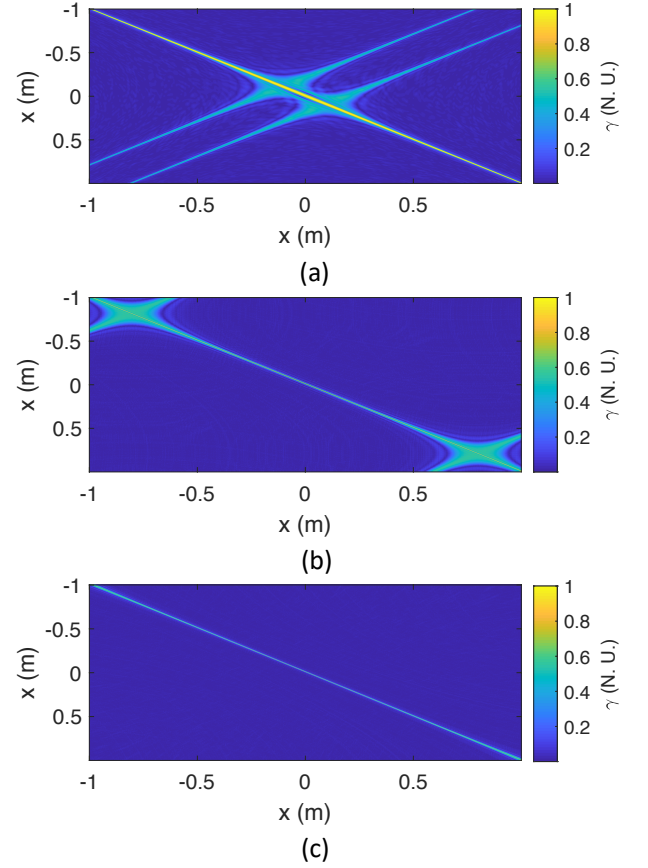


Figure 2. (a) Far field illumination using 2 incoherent noise transmitters which shows partial coherence lines with $\gamma = 1/2$ (b) Fresnel-zone illumination using 2 incoherent noise transmitters. The partial coherence lines have been pushed at the edges of field of view. (c) Near field illumination using 2 incoherent noise transmitters. The partial coherence lines have been pushed outside the field of view of the image reconstruction achieving perfect spatial incoherence inside the field of view.

it can be seen in Fig. 2(c). All the points along the line have unique phase responses which is the ideal scenario for active incoherent illumination and will minimize the artifacts in the spatial frequency sampling process.

These first results represent a promising approach to synthesize space-time incoherent illuminations for active incoherent millimeter-wave imaging. Far field illuminations can appear partially coherent for a small number of transmit elements. Fresnel zone illuminations seem to push the partial coherence lines at the edges of the field of view, away from broadside. Near field transmit configurations seem to achieve perfect incoherence broadside of the array. Future work will include spatial tailoring of the partial coherence lines along with analytic derivations and bounds.

3 Conclusion

The spatial coherence from incoherent transmitters at different radiating zones has been analyzed in this article. Compared to far field incoherent illumination that can exhibit a worst case spatial incoherence of $1/N$ when using N transmitters, near-field can achieve close to perfect incoherence using only 2 transmitters for 1-D imaging.

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