Statistical Analysis of Optical Up-Conversion Passive Imager Receiver and Image Quality

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ABSTRACT

Passive millimeter and terahertz wave imaging have emerged as a promising human security screening and scene surveillance technique. Due to the minimal contrast in brightness temperatures between the human body and concealed objects, enhancing the temperature sensitivity and spatial resolution of radiometers remains challenging. The measure of system sensitivity is noise equivalent temperature difference (NEΔT) and probability of detection (Pd). While conventional RF receivers down-convert the received signal using a mixer and local oscillator for image rendering, herein we present the latest developments of a state-of-the-art optical up-conversion receiver that up-converts the received RF signal onto the sideband of an optical carrier across a phased array antenna. After up-conversion, each signal is routed back to an optical fiber bundle that is subsequently spatially Fourier-transformed using a lens to render an image. In this presentation, a theoretical study and system-level simulations are used to illustrate the efficacy of this approach in terms of Pd.

Keywords: Passive mmW imaging, noise equivalent temperature, probability of detection

1. INTRODUCTION

The usefulness of mmW imaging originated from the emission of mmW from all objects above 0 K and the low propagation losses through common obscurants such as haze, cloud, smoke, dust, dry leaves, and thin layers of dry soil. Various schemes have been proposed to realize mmW imaging reconstruction, most of which are based on mmW focal plane approaches. [1, 2] We proposed a passive millimeter wave interferometric imaging system using an optical up-conversion process. [3-5] The system leverages our high-speed Lithium Niobate (LiNbO3) electro-optic (EO) phase modulators that are inherently broadband (DC to > 300 GHz) to upconvert received millimeter-wave fields onto an optical carrier efficiently such fields can be readily captured, routed, and processed using optical techniques, thereby providing significant advantages over traditional heterodyne imagers. [6] Even though the proposed system has demonstrated its unique advantages in many aspects, particularly in the reduction of size, weight, and power (SWaP). However, the ultimate limits on sensitivity depend on noise; the final performance can only be predicted using statistical means that properly account for each fluctuating effect.

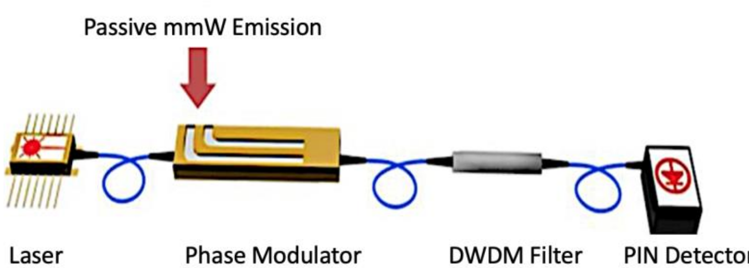

Figure 1. Single pixel realization of optically based millimeter-wave detection process.

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2. STATISTICAL MODEL

Statistical Model and Image Quality

NEΔT (Noise Equivalent Delta Temperature) and Pd (Probability of Detection) are critical parameters in thermal imaging that greatly influence image quality across various processing techniques such as denoising, segmentation, contrast enhancement, and edge detection. A lower NEΔT value indicates that the sensor can detect smaller temperature differences above the noise level, which is crucial for producing clearer images, especially for scenarios where the difference in temperature between an emitting object and a human body is very narrow. This improved signal clarity enhances the effectiveness of object detection and enhanced contrast. On the other hand, Pd is essential for ensuring that genuine thermal variations in the scene are accurately captured and not dismissed as noise, which is vital for maintaining detail integrity during denoising [7]. High Pd ensures that these differences are detected reliably, reducing the chances of misclassification and enhancing the segmentation accuracy.

New Statistical Model

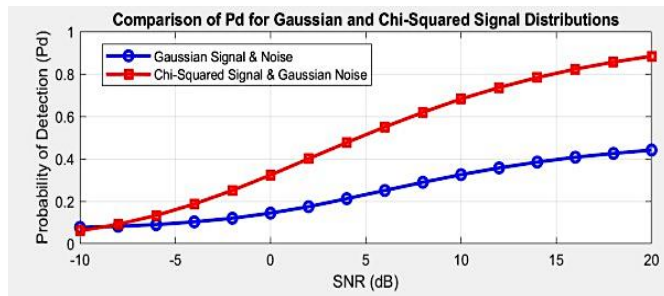

Figure 2 A comparison between Heterodyne and Optical up-conversion receivers' performance in terms of probability of detection over a range of SNRs

A heterodyne receiver statistical model was previously analyzed, and a pdf for the model was driven. This is a Rayleigh distribution for noise only due to the mixing of AWGN with the local oscillator before detection. Similarly, the signal and LO mixture will yield Rician distribution [7]. However, the topic of optical up-conversion passive receivers wasn't equally covered. Passive mmW emission is often regarded as a broadband source low-coherence optical source based on spontaneous emissions. A key property of a coherence source when spectral (such as in filtering) is the presence of spectral slicing noise [8]. The detection of such a source generates a spontaneous spontaneous beat noise. When the optical bandwidth of the broadband source is sufficiently increased, the spontaneous-spontaneous beat noise becomes negligible because of the large optical bandwidth. However, when the optical bandwidth is significantly reduced, it becomes dominant over electrical noise and limits the channel capacity. Perhaps counterintuitively, the SSN increases as the optical bandwidth of the signal, Bo, decreases to approach the electrical bandwidth of the receiver, be (because the decrease in optical bandwidth concentrates SSN power over a narrower range of frequencies). Square-law detection of SSN is most accurately modeled as the Chi-squared distribution with M degrees of freedom, where M is the number of modes per polarization state in the received optical spectrum. Since spontaneous-spontaneous beat noise is a random process in the frequency domain, standard normal random variables forming the emission are zero-mean independent Gaussian random variables, with variance $\frac{N_O}{2}$, the sum of their squares is distributed according to the Chi- squared distribution with 2M degrees of freedom. That is the basic definition of the Chi-squared distribution. The
corresponding noise probability density function is given by:

$$p(x)=\frac{\frac{1}{N_o}\left(x/N_o\right)^{M-1} e^{\frac{-x}{N_o}}}{(M-1)}, x>0 \tag{1}$$

3. SIMULATIONS

Pd

In the Gaussian signal and noise scenario, the received signal forms a symmetrical Gaussian distribution around its meaning. In the Chi-Squared signal scenario, the received signal distribution becomes skewed due to the nature of the Chi-Squared distribution, showing a longer tail towards higher values and a sharp transition towards 0 at 0. This leads to a much better probability of detection in the Chi-Squared case. Since the Chi-Squared distribution always goes to 0 at 0, that automatically means a better probability of detection, as demonstrated in Fig.2.

Image Quality

The histograms illustrate the distribution of the received signal in each case. The received signal forms a Rician distribution around its mean for the Heterodyne case. In the Chi-Squared signal scenario, the received signal distribution becomes skewed due to the nature of the Chi-Squared distribution, showing a longer tail towards higher values and a sharp transition towards 0 at 0. This leads to a much better probability of detection in the Chi-Squared case. Most obvious fluctuations have been reduced. The metal object (aluminum cylinder) has the lowest brightness temperature, which is about equal to the ambient physical temperature. So, the contrast between the human body and the background is more obvious, with less noise, as shown in Fig 3.

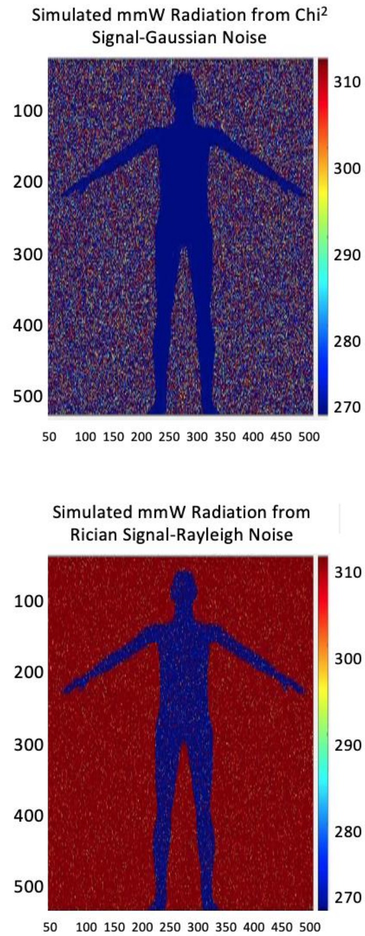

Figure 3 Simulated Images showing that Optical Up-Conversion Receiver have a better advantage denoising without losing that much image information

4. CONCLUSION

The study highlights the significance of Pd in thermal imaging, where higher Pd ensures accurate detection of genuine thermal variations. A statistical analysis comparing heterodyne and optical up-conversion receivers reveals that the Chi- squared noise model used in optical up-conversion offers a better probability of detection due to its skewed distribution, which reduces misclassification.

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