Research Article

Performance Analysis of Ultra-Wideband Channel for Short-Range Monopulse Radar at Ka-Band

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High-range resolution is inherently provided with Ka-band ultra-wideband (UWB) vehicular radars. The authors have developed a prototype UWB monopulse radar equipped with a two-element receiving antenna array and reported its measurement results. In this paper, a more detailed verification using these measurements is presented. The measurements were analyzed employing matched filtering and eigendecomposition, and then multipath components were extracted to examine the behavior of received UWB monopulse signals. Next, conventional direction finding algorithms based on narrowband assumption were evaluated using the extracted multipath components, resulting in acceptable angle-of-arrival (AOA) from the UWB monopulse signal regardless of wideband signals. Performance degradation due to a number of averaging the received monopulses was also examined to design suitable radar's waveforms.

1. Introduction

Ultra-wideband (UWB) vehicular radars, recently approved by governments of many countries, are expected to be instrumental in reducing traffic accidents [1]. In comparison with conventional vehicular sensing systems using ultrasound, visible and infra-red light, and millimeter waves, Ka-band UWB radar systems hold several advantages, such as no blind angle [2], high-resolution in ranging, weatherproof, and lower price than millimeter-wave radars. Since transmission power of UWB systems is restricted at a level low enough to avoid interference with conventional narrowband systems, UWB vehicular radars are used at short range for collision warning, blind spot detection, parking aid, and precrash control.

During the last decade, there has been much progress on UWB technologies. To understand the behavior of UWB signals, the UWB propagation channel is measured and characterized as described in [3]. Different channel models for practical UWB systems have been proposed in multipath environments [4–6]. Since UWB signals potentially have high resolution in ranging, the different UWB ranging

systems, in multipath environments, have been investigated in [7, 8].

The UWB signals for the vehicular radar have also been measured and modeled in some ways: a generic stochastic uniformly tapped delay line model of multipath UWB channel [9], outdoor channel modeling based on measurements by means of a vector network analyzer [10, 11], and a pulse-based UWB sensor [12]. However, it is insufficient to characterize the behavior of UWB channel signals for short-range monopulse radar at Ka-band, since these works focus on generic modeling below Ka-band. Ranging and direction finding are a key feature of UWB radar systems. Thus, we need to understand these characteristics for Ka-band using a practical analysis method based on measurements.

The authors have developed a prototype UWB monopulse radar equipped with a receive two-element antenna array. The performances of ranging and direction finding by delta-over-sigma (DOS) scheme were evaluated using measurements obtained in a radio anechoic chamber and outdoor environments [13]. However, several problems arise when analyzing the performance of this radar setup. First, the DOS scheme uses sum and differential signals impinging

FIGURE 1: Train of transmitted monopulses.

on the two-element array. A predetermined broadside is required for the DOS scheme to estimate angle-of-arrival (AOA) even if the radar moves toward different directions. Moreover, the DOS scheme specialized to a two-element array makes it impractical as an implementation for general multielement antenna array.

Since the measurements were conducted with independent reception for DOA scheme at each of the two-element array, the prototype UWB monopulse radar could not be collected enough of received signals. We, therefore, developed an analysis technique to model UWB monopulse signals by focusing on two ways to understand characteristics of ranging and direction finding, regardless of some constraints. First, the measurements were analyzed to characterize the behavior of multipath components from a target contained in the received signals. Next, instead of applying the DOS scheme, conventional techniques of pulse compression for ranging and multiple signal classification (MUSIC) or minimum variance distortionless response (MVDR) algorithms for direction finding were adopted to evaluate the applicability in UWB vehicular radars. The obtained results provide insight into UWB monopulse radar design.

The rest of this paper is organized as follows: modeling multipath components is discussed in Section 2. Experimental verification of the prototype radar from measurements in a radio anechoic chamber is described in Section 3. Performance analysis of the UWB monopulse signals in outdoor environments is presented in Section 4. Finally, the conclusions are drawn in Section 5.

2. Modeling Multipath Components

The UWB monopulse radar can resolve more multipath components than conventional narrowband radar systems because of its high resolution in ranging. Moreover, the AOA of each of the components is obtained if multiple-element antennas are adopted and conventional direction finding algorithms are available. However, an optimum analysis scheme for the received signal is required to design reliable UWB radar systems with acceptable performance. We then derive the detection scheme for resolvable or nonresolvable multipath components within received UWB monopulse signals.

2.1. Resolvable Multipath Components. A train of transmitted monopulses demonstrated in this work is shown in Figure 1. There is a single monopulse in each pulse repetition interval (PRI). The signal impinging on the target and the reflected signal observed by the receive array are assumed to be

plane waves in a static channel. If M signals impinge on the L -element array from distinct AOAs, the received signal commonly used in array processing is given by [14]

$$\mathbf{x}(t) = \mathbf{A}(\boldsymbol{\theta})\mathbf{s}(t) + \mathbf{n}(t), \quad (1)$$

where a steering matrix $\mathbf{A}(\boldsymbol{\theta})$ and a vector of signal waveforms $\mathbf{s}(t)$ are defined by

$$\begin{aligned} \mathbf{A}(\boldsymbol{\theta}) &= [\mathbf{a}(\theta_1), \dots, \mathbf{a}(\theta_M)], \\ \mathbf{s}(t) &= [s(t), \dots, s_M(t)]^T. \end{aligned} \quad (2)$$

Assuming a uniform linear array (ULA) having interelement spacing of d , a steering vector $\mathbf{a}(\theta_m)$ can be written by

$$\mathbf{a}(\theta_m) = [a_1(\theta_m), \dots, a_L(\theta_m)]^T, \quad m = 1, \dots, M. \quad (3)$$

For the plane wave case, l -th elements at the AOA θ_m are given by

$$a_l(\theta_m) = e^{-j(l-1)(2\pi/\lambda)d \sin \theta_m}, \quad l = 1, \dots, L, \quad (4)$$

where λ is wavelength.

The received signals are assumed as discrete signals, and then the received signal matrix per PRI can be written as

$$\mathbf{X} = [\mathbf{x}(1), \dots, \mathbf{x}(N_{\text{pri}})], \quad (5)$$

where N_{pri} is a number of signal samples per PRI. A pulse compression can be carried out for each element output to detect multipath components passed through a matched filter. This output of l -th element is simply the inner product between received signals of l -th element and replica signals, namely, pulse compression [15], as given by

$$r_l(n) = \mathbf{X}_l(t_n) \cdot \mathbf{h}, \quad (6)$$

where $t_n = n+1, n+2, \dots, n+N_{\text{pri}}-N_{\text{seq}}, n = 0, 1, \dots, N_{\text{pri}}-N_{\text{seq}}$, and $\mathbf{h}$ is a complex conjugate column vector of the replica signal with length of N_{rep} . Thus, all of the $N_{\text{pri}}-N_{\text{seq}}+1$ outputs are obtained for each PRI, and then the outputs of the l -th element are averaged over N_{ave} PRIs:

$$\bar{r}_l(n) = \frac{1}{N_{\text{ave}}} \sum_{a=1}^{N_{\text{ave}}} r_{l,a}(n). \quad (7)$$

Finally, k th multipath components can be extracted to choose the signal strength higher than the optimum threshold γ , as given by

$$|\bar{r}_l(n_k)| > \gamma, \quad k = 1, 2, \dots, K, \quad (8)$$

where n_k is a delay sample from the PRI boundary of the k -th multipath components. Therefore, for a static environment, the total of K peaks can be related to the resolvable multipath components.

FIGURE 2: The block diagram of the prototype radar transmitter-receiver.

2.2. Nonresolvable Multipath Components. We next consider how to detect nonresolvable multipath components. The sample covariance matrix is calculated using $2N_{\text{smp}} + 1$ samples around k -th resolvable multipath components:

$$\mathbf{R}_k = \frac{1}{2N_{\text{smp}} + 1} \mathbf{X}(n_i) \mathbf{X}^H(n_i), \quad (9)$$

where $n_i = n_k - N_{\text{smp}}, n_k - N_{\text{smp}} + 1, \dots, n_k, \dots, n_k + N_{\text{smp}}$.

Up to this point, an arbitrary number of array elements have been discussed. In subsequent discussions, we focus on an $L = 2$ case since a two-element array was implemented in our prototype radar system. Two eigenvalues λ_1 and λ_2 can be obtained from eigendecomposition of $\mathbf{R}_k$, because $\mathbf{R}_k$ is guaranteed positive definite due to Hermitian matrix. There are three types of eigenvalue distribution: $\lambda_1 \geq \lambda_2 > \sigma^2$ when two or more signals having different AOAs impinging on the receive array, or a single AOA cannot correctly resolve owing to inadequate accuracy of the elements in $\mathbf{R}_k$, where σ^2 is a noise variance; $\lambda_1 > \lambda_2 = \sigma^2$ when a single signal impinges on the receive array; $\lambda_1 = \lambda_2 = \sigma^2$ when none of signals is received.

Nonresolvable multipath components within each multipath component will be estimated from this classification because of the Nyquist rate. The basic idea is to find a criterion of nonresolvable multipath components from measurements collected in a single-path environment realized in radio anechoic chamber. The criterion can be obtained to apply the second type of eigenvalue distribution. Specifically, the nonresolvable multipath component can be estimated if λ_2 is larger than the boundary, since a boundary between resolvable and nonresolvable multipath components is determined from the distribution of λ_2 . Hence, the behavior of a multipath component in outdoor environments is characterized when using a passenger vehicle as a target. This criterion can be easily extended to an array having elements more than 2.

3. Anechoic Chamber Experiments

3.1. Experimental Setup. The block diagram of a prototype Ka-band UWB pulse radar is depicted in Figure 2, which is the same system as our previously published work [13], except that the received signals were directly input to an IQ demodulator without passing through a coupler. The experiment was set for a single-path environment in a

TABLE 1: Specification of experiments.

Waveform	Modulated Gaussian monopulse
Pulse duration	1 ns
Frequency bandwidth	24.0–29.0 GHz
Sampling rate	10 or 20 Gsps
Antennas	Slot antennas
Polarization	Vertical-vertical
Element spacing	5.4 mm
Spectrum density of average emission	< −44 dBm/MHz

radio anechoic chamber. The measurements were analyzed to obtain parameters required to characterize resolvable or nonresolvable UWB monopulse signals in outdoor environments. Gaussian monopulse has been widely adopted for UWB systems to satisfy FCC spectrum mask regulations [16]. Various practical monopulse design techniques have been developed in [17–19]. The performance of these design techniques has also been analyzed in different ways: principle of space-time array processing [20], target recognition reflected on different obstacles [21], and position estimation [22]. We also adopted Gaussian monopulse due to its ease of use with our analysis methods. An arbitrary waveform generator with a sampling rate of 25 GHz was used as an impulse generator.

In the first experiment, a trihedral corner reflector was used as a target, comprising three right-angled isosceles triangles with 210 mm long sides. Its radar cross section was approximately 191 m². The reflector was placed at a distance of 2.8 m from the radar. The radar was rotated from -30° to 30° in intervals of 1° , and then received signals were recorded. A direction of 0° was defined as broadside of the two receive antennas. Transmit and receive antennas were slot antennas with vertical polarization. The impulse generator outputs baseband Gaussian monopulse trains with monopulse duration of 1 ns occupying a bandwidth of 2 GHz, as shown in Figure 3. The trains are upconverted through RF modules by a carrier frequency of 26.5 GHz and emitted from the transmitting antenna. The spectrum density of the average emission in this band was selected less than −44 dBm/MHz to satisfy FCC regulations [1]. Each received signal impinging on the two-element array is down-converted to baseband by the IQ demodulator, analog-to-digital converted at a sampling rate of 10 or 20 Gsps, and then recorded in a digital storage oscilloscope (DSO). The transmitted and received UWB monopulse signals are shown in Figures 3(a) and 3(b), respectively. The latter is distorted due to mismatching in the RF components. Major parameters of the experiment are listed in Table 1.

The above setup is capable of collecting data of the single path impinging on a horizontally placed two-element array with half-wavelength element spacing. The received signal performance and the results for analyzing the measurements are described in the next section.

FIGURE 3: Baseband monopulse waveforms.

A received signal power typically attenuates as the distance between the radar and the target increases. Hence, resolution accuracy of ranging and direction finding will depend on the received power. A technique that averages received monopulses is useful to increase received signal gain without increasing transmit power. We then estimated the resolution accuracy by evaluating the different numbers of averaging monopulses at the receiver. The result is discussed in Section 4.5.

3.2. Performance Analysis. Received multipath components, after averaging over 10^4 PRIs, were extracted by pulse compression, as given by (7). The reference signals of the matched filter used for both the I and Q channels were the received monopulse signal shown in Figure 3(b). The pulse-compressed output when the radar is directed to 0° is shown in Figure 4, where a single sharp peak is observed. The plot shows that the number of averaging 10^4 PRI is sufficient to extract a single peak from the noisy received signals, and the outputs directed to the other angles also have a single peak. However, since the antenna pattern is not isotropic, the peak strength decreases as the direction moves away from broadside. The peak strength from -30° to 30° is shown in Figure 5.

Next, the covariance matrix $\mathbf{R}$ and its eigenvalues were calculated for each extracted peak, as described in Section 2.2. To collect more samples around the peak, $N_{\text{smp}} = 2$ (total 5 samples) was selected for 20 Gsps sampling. The obtained 61 pairs of eigenvalues λ_1 and λ_2 were then normalized by λ_1 . The eigenvalue distribution shown in Figure 6 revealed that all the λ_2 are sufficiently smaller than unity regardless of direction. It is thus concluded that λ_1 is a signal or resolvable component and λ_2 is a noise or nonresolvable component, and its boundary is 10^{-1} . This boundary will be used as the criterion of detection of nonresolvable multipath components in the outdoor experiments, as described in Section 4.2.

Finally, the AOA was estimated for each of the extracted peaks using MUSIC algorithm [14] to verify its applicability to the UWB monopulse signals. The obtained AOAs are plotted in Figure 7. The two regression curves corresponding

FIGURE 4: Pulse-compressed output signals from broadside in anechoic chamber experiments.

FIGURE 5: Magnitude of extracted multipath components corresponding to different angles in anechoic chamber experiments.

FIGURE 6: Normalized eigenvalue distribution derived from the measurements in anechoic chamber experiments.

FIGURE 7: Estimated AOA by MUSIC derived from the measurements in anechoic chamber experiments.

to plus and minus angles are also plotted by solid lines. The plot shows that the MUSIC algorithm can be utilized for UWB signal with monopulse duration of 1 ns and carrier frequency of 26 GHz. This result can prove that the carrier-to-baseband frequency ratio of 26 is sufficient for the conventional direction finding algorithm regardless of the UWB signals.

4. Outdoor Experiments

4.1. Experimental Setup. The next experiment was conducted in outdoor environments. A four-door sedan, 4.73 m long, 1.80 m wide, and 1.44 m high, was used as a radar target in the outdoor experiment. The vehicle, parked on a broadside, is shown in Figure 8. The different locations

FIGURE 8: A radar target on a broadside in outdoor experiments.

FIGURE 9: 57 locations of a target vehicle in outdoor experiments.

of the target vehicle are illustrated in Cartesian coordinates (x, y) in Figure 9. Placing the radar at the origin of the center lane, the vehicle was parked at 57 locations between the left, center, and right lanes. The 57 locations were corresponded to a target direction with an azimuth angle θ_i between -42° and $+42^\circ$ and a target distance d_i from 2.9 m to 10 m away from the origin, where $i = 1, \dots, 57$. The center of the rear bumper was used to define the target direction and distance, since the transmitted signals mainly impinged on the back of the target vehicle. The height of the radar antennas was

FIGURE 10: Pulse-compressed output signals from broadside in outdoor experiments.

FIGURE 11: Normalized eigenvalue distribution derived from the measurements in outdoor experiments.

0.6 m, which was the same as that of the rear bumper. Effects of surrounding trees and buildings were negligible because the signals reflected from the vehicle were dominant in this setup.

Since there were no obstructions between the radar and the target vehicle, the channel model associated with this setup is line-of-sight (LOS) channel. Assuming a narrow-band signal, the LOS path is given by a single propagation path because of low time resolution that is less than the inverse of the signal bandwidth. Whereas for the UWB signal, multipath components reflected from the target can be resolvable, so that every resolvable delay bin does not contain multipath components [3]. Moreover, the multipath components impinging on the antenna array are confined to

small angle and delay corresponding to the target vehicle. This implies that the collected measurements are no longer treated as the specific channel models. We then characterize the UWB channel as the delay bin having either resolvable or nonresolvable multipath components, as described in the next section.

4.2. Resolvable/Nonresolvable Multipath Components. Multipath components were extracted for received signals by pulse compression given by (7). The obtained pulse-compressed output from the broadside and at a distance of 3.6 m, namely, power delay profile, is shown in Figure 10. The resolvable multipath components were extracted to select the K largest peaks as in (8) and then classified as three regions with respect to the lane of the parked vehicle: the left with minus angle, the center with the broadside, and the right with plus angle. The extracted number of multipath components was averaged over each region. The mean value on the broadside was the largest value at 5.1, while those in the left and right regions were, respectively, 3.0 and 4.1. This is because when the multipath components arriving from different directions have the same delay, the signal strength on the broadside is higher than that in the other regions, as shown in Figure 5. Therefore, the number of extracted peaks, depending on signal strength, decreases as the target direction moves away from the broadside.

Next, the nonresolvable multipath components within the extracted resolvable multipath components were evaluated. Setting $N_{\text{smp}} = 2$ and calculating the covariance matrix $\mathbf{R}$ as described in Section 2.2, two eigenvalues λ_1 and λ_2 were obtained by eigendecomposition of $\mathbf{R}$. The eigenvalue distribution normalized with λ_1 is illustrated in Figure 11. It is observed that some of eigenvalues λ_2 are larger than 10^{-1} ; the detection boundary was described in Section 3.2. Thus, the resolvable multipath component having λ_2 larger than 10^{-1} can be defined as a nonresolvable multipath component, as described in Section 2.2.

The number of nonresolvable components was also averaged in each region, and then the ratio of the number of nonresolvable components to that of resolvable components was calculated. The obtained ratios in the left region, on the broadside, and in the right region were 7.6%, 8.7%, and 6.9%, respectively. The nonresolvable multipath components are observed to concentrate on the broadside. This is because the multipath components, having a smaller delay than the monopulse duration of 1 ns, tend to impinge on the receive array when the array is placed parallel to the four sides of the vehicle. In this experiment, a vehicle located on the broadside is parallel to the receive array, as shown in Figure 8.

4.3. AOA Estimation. The AOA was also estimated for each extracted peak using the MUSIC and the MVDR algorithms [8] used in the second experiment. The AOAs for the MUSIC versus the target direction are illustrated in Figure 12. A similar plot is obtained by MVDR algorithm. The two regression curves calculated from the anechoic chamber experiments are also plotted by solid lines. Note that the AOAs from the right region have an offset from the regression

FIGURE 12: Estimated AOA by MUSIC derived from the measurements in outdoor experiments.

curve; this may be attributed to antenna misalignment. It can be seen that the AOAs from the target direction between -20° and $+20^\circ$ are close to the regression curves. Because of the resolution limitation caused by the two-element array and the anisotropic antenna radiation pattern, the number of outliers increases as the target angle moves away from the broadside.

4.4. Ranging and Multipath Spread. A UWB signal enables precision ranging capabilities because of a time resolution on the order of 1 ns [23]. The ranging of each location is obtained by finding the largest peak in the measured power delay profile. This approach is similar to a threshold-based energy detector-based time-of-arrival estimator [7] because a preamble structure resembles the transmitted pulse trains as shown in Figure 1. Since the delay from the PRI boundary to the largest peak is round-trip time between the origin and the target vehicle, the ranging is obtained from half of the delay time, as given by

$$\hat{d}_i = \frac{cT_i}{2}, \quad i = 1, 2, \dots, 57, \quad (10)$$

where c is the light velocity and T_i is the delay bin of the i th location. Each reference distance between the origin and the i th location was measured from the receive array to the center of the vehicle on the rear bumper. The standard deviation of the ranging errors at each location versus the target distance is shown in Figure 13. The ranging resolution of 0.15 m corresponding to the monopulse duration of 1 ns is also plotted in a solid line. A single outlier more than the ranging resolution of 0.15 m is observed regardless of the shortest target distance. This phenomenon is also explained by the magnitude of extracted multipath component, as shown in Figure 5. Since the magnitude decreased as the target direction moved away from the broadside, the multipath component corresponding to the rear bumper center could not be precisely extracted at the location with the largest target direction. In other words, the largest peak of measured

FIGURE 13: Standard deviation of ranging errors in outdoor experiments.

power delay profile did not always arrive from the rear bumper center when the target vehicle moved away from the broadside.

Thus, it seems intuitive that the obtained power delay profile from the target vehicle contains mostly reflected path components around the rear bumper center. We next estimate the propagation paths arriving from the target vehicle, and then define a multipath spread of the profile as a difference between the shortest and the largest arrival distances of multipath components to estimate the reflection point corresponding to each multipath component. The multipath spread of each target location is a plotted 3D graph, as shown in Figure 14. The resulting spread on the broadside ranges from 0.29 to 0.5 [m], so the distance is too long to generate the power delay profile from only directly reflected path components from the rear bumper. Therefore, from the rear surface of the vehicle shown in Figure 8, the reflection points of multipath components may include the pillar and roof as well as the bumper and the ground reflection path as well as the direct path. On the other hand, the multipath spread in the left and right regions tend to decrease as the target distance increases and target angle moves away from the broadside. This is mainly due to two reasons. First, since the side of the vehicle enables to contribute the reflection, the width of probable reflection surface increases as target angle moves away from the broadside. Second, the width of probable reflection surface on the vehicle decreases in proportion to distance and then more than one multipath component with almost the same delay tends to fall in a single peak.

4.5. Effect of Number of Averaging PRIs. The analyses so far has used the measurements with the averaging of 10^4 PRIs and a sampling rate of 20 Gsps. The number of PRIs is an

FIGURE 14: Multipath spread from a target vehicle in outdoor experiments.

FIGURE 15: Pulse-detection probability versus number of averaging PRIs in outdoor experiments.

important parameter to improve accuracy of practical radar systems. The signals of each PRI were also recorded on the DSO with a sampling rate of 10 Gsps at the locations, as shown in Figure 9. The recorded signals were averaged over N_{ave} PRIs, where $N_{ave} = 16, 32, 64, 128$, and 149 , since the maximum number of PRIs was 149 owing to the limitation of memory size on the DSO with 10 Gsps sampling. Note that when calculating $\mathbf{R}$, $N_{smp} = 1$ (total 3 samples) was selected for 10 Gsps sampling.

For the measurements of 20 Gsps sampling, the ranging accuracy was verified as described in Section 4.4. We then define a ratio of correctly estimated ranging at each location as a pulse-detection probability. For example, the pulse-detection probability for averaging of 10^4 PRIs was unity, since the estimated ranging error was zero. The resulting

pulse-detection probability versus the averaging N_{ave} is plotted in Figure 15. The regression curve is also plotted. The probability increases with N_{ave} because of improvement of signal-to-noise ratio by averaging. The AOAs were next evaluated using only the multipath components corresponding to the correctly estimated ranging. However, almost all AOAs are not accurately estimated for N_{ave} less than or equal to 128 . These results show that the level of the extracted peak after the pulse compression is generally below that of noise and thus; time average cannot converge to the true mean value.

5. Conclusions

This paper has presented the multipath resolution and direction findings of a UWB monopulse radar equipped with a two-element array. We cannot perform more detailed analyses owing to experimental limitations, such as the number of array elements, the number of monopulses per PRI, the received monopulse distortion, and measuring in static environment only. However, since the obtained results are useful parameters for performance analysis by computer simulation, a more practical UWB monopulse radar with multiple-element array will be designed. Moreover, the proposed estimation methods for resolvable/nonresolvable multipath components will be a valuable tool for any other UWB monopulse radars. The number of averaging monopulses is an important parameter for accuracy of ranging and direction finding. However, the observations must be corrected in static or quasistatic environments. Therefore, for practical use, a number of monopulses per PRI, sampling rate, and multiple-element array must be considered to increase the number of observations as quickly and accurately as possible.

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