Interference Suppression Performance of Automotive UWB Radars Using Pseudo Random Sequences

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Abstract. *Ultra wideband (UWB) automotive radars have attracted attention from the viewpoint of reducing traffic accidents. The performance of automotive radars may be degraded by interference from nearby radars using the same frequency. In this study, a scenario where two cars pass each other on a road was considered. Considering the utilization of cross-polarization, the desired-to-undesired signal power ratio (DUR) was found to vary approximately from -10 to 30 dB. Different pseudo random sequences were employed for spectrum spreading the different radar signals to mitigate the interference effects. This paper evaluates the interference suppression provided by maximum length sequence (MLS) and Gold sequence (GS) through numerical simulations of the radar's performance in terms of probability of false alarm and probability of detection. It was found that MLS and GS yielded nearly the same performance when the DUR is -10 dB (worst case); for example when fixing the probability of false alarm to 10^{-4}, the probabilities of detection were 0.964 and 0.946 respectively. The GS are more advantageous than MLS due to larger number of different sequences having the same length in GS than in MLS.*

Keywords

UWB, radar, maximum length sequence, Gold sequence, interference suppression, detection probability

1. Introduction

Ultra wideband (UWB) automotive radars are receiving huge research interests for its potential to be applied as automotive radars that could assists drivers, as well as automated driving applications [1]. In comparison with conventional vehicular sensing system using infra-red, ultra-sound, and millimeter-waves radar, the Ka-band UWB radar systems hold several advantages such as reduced blind-angle [2], high range resolution, robustness to weather conditions, and lower costs than millimeter-wave radars. Nevertheless, if the environment is populated by cars equipped with independent automotive radars, the performance of each radar will be degraded by interference signals entering their receivers, which are originated from nearby radars operating at the same frequency. The performance degradation can be mitigated with the use of cross-polarization and code division multiple access (CDMA) technology [3–5], however, quantitative evaluation of interference suppression have not been fully exploited. The authors previously studied the interference rejection capability of automotive radars modulated by maximum length sequence (MLS) codes [6], and derived the basic capability of the method to suppress interference.

In this paper, we further investigated the interference suppression performances of UWB automotive radars modulated by pseudo random sequence using binary MLS, and Gold sequences (GS). Both sequences were selected due to their good auto- and cross-correlation properties, which is significantly useful in suppressing interference from nearby radars. Initially, the desired-to-undesired signal power ratio (*DUR*) was examined when two cars pass by each other on the opposite side of the road. Suppression of interference was numerically evaluated by calculating the probability of false alarm (P_{fa}), and the probability of detection (P_d) of the radar for the estimated *DUR*. Important characteristics of both sequence which is related to the automotive radar system design was also discussed, such as the order of shift register, code length, number of available sequence, and auto- and cross-correlation properties.

2. Calculation of Desired-to-Undesired Signal Power Ratio

We estimated the *DUR* while assuming a scenario where two cars pass each other on a road. Both cars are equipped with UWB radars aiming horizontally and 60° from the axial direction of travel of the cars, as depicted in Fig. 1. The desired signal power *D* is the receiving radar signal emitted from its own transmitter and reflected from the oncoming car; and the undesired signal power *U* is the interference signal entering the receiver from the other radar equipped on the oncoming car. Here, *D* and *U* are
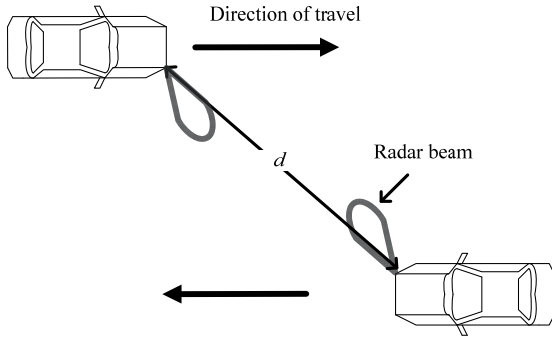
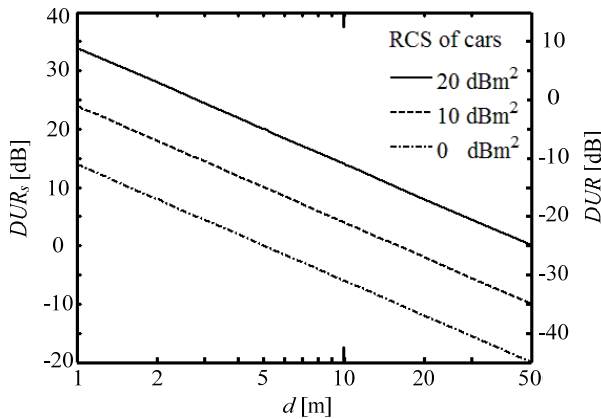**Fig. 1.** Scenario for evaluating a range of *DUR*.

Fig. 2. Substantial DUR_s against the distance between two cars, assuming 45°-polarization for transmission and reception.

expressed by:

$$D = \frac{P_t G_t(\theta) G_r(\theta) \lambda_0^2 \sigma}{(4\pi)^3 d^4} \quad \text{[W]}, \qquad (1)$$

and

$$U = P_t G_t(\theta) G_r(\theta) \left(\frac{\lambda_0}{4\pi d}\right)^2 \quad \text{[W]} \qquad (2)$$

where P_t is the transmitting power, G_t the antenna gain for transmission and reception, G_r the azimuth angle from the antenna boresight, λ the wavelength and σ the radar cross section (RCS) of targets, and d the distance between the two cars. Therefore, the *DUR* is expressed by

$$DUR = 10\log\left(\frac{D}{U}\right) = 10\log\left(\frac{\sigma}{4\pi d^2}\right) \text{ [dB]}. \qquad (3)$$

Here, we could understand from (3) that the *DUR* is independent of P_t, $G_t(\theta)$, $G_r(\theta)$, and when the two radars transmit the same power and use the same antennas. Equations (1) to (3) were derived based on free space (FS) model consideration. This is based on calculations of first Fresnel zone radius (refer Appendix) and assumptions that the directivity of antenna beam was optimized for vehicular applications. Furthermore, UWB two-ray propagation model reported in [7] indicated that frequency diversity effects reduced the fading depth from two-ray interference for the case of UWB, approximating the case of FS propagation. Hence, we considered the FS model in this study.

The RCS of a typical passenger car ranges from 2 to 20 dBm² [2], and d varies from 1 to 20 m, considering the lane widths of roads range from 2.8 to 3.5 m. It is important to note that we used a simplified assumption of UWB RCS based on investigation in [2]. Precise estimation of UWB RCS for cars may require considerations of antenna height and wavelength, however, the authors limit the scope of the paper to evaluating the radar performance, and will address the mentioned problem in a separate work.

If the two radars utilize vertical and horizontal polarization, the *DUR* lies between -35 and 9 dB. Since the *DUR* of -35 dB (when $\sigma = 2$ dBm² and $d = 20$ m) is too low to discriminate between the desired and undesired signals, we further assume that the radars use 45°-inclined linear polarization. In this case, the desired signal is received in 45° polarization, while the undesired signal in −45° polarization. Here, assuming the cross polarization discrimination of the antennas to be *XPD* dB, the substantial *DUR* (DUR_s) is therefore enhanced by

$$DUR_s = DUR + XPD. \qquad (4)$$

Here, we consider the typical *XPD* of linear polarized antennas such as slot and microstrip patches exceeds 25 dB. Therefore, the DUR_s ranges approximately from -10 to 34 dB. The plot of DUR_s against distance d is shown in Fig. 2.

3. Simulation Setup

3.1 Pulse Trains Modulated with Maximum Length- or Gold-Sequences

The UWB radar under consideration transmits a series of UWB pulses which is modulated by pseudo random sequence consisting of binary phase shift keying (BPSK) codes with either MLS or GS. The pulse waveform can be arbitrarily selected to comply with UWB spectrum mask specified by regulatory bodies. When the radar is using pulses with duty cycle $\tau_d = 133$ ns, for example, the detection range $R = c \tau_d/2 = 20$ m, where c is the electromagnetic wave velocity. The time interval for alarming the driver was set to be 100 ms, considering normal human reaction time [8]. During this 100 ms, the radar is capable to transmit 750,000 pulses (= 100 ms / 133 ns).

For the case of MLS, the codes are generated with a k-stage feedback shift register, resulting in $2^k - 1$ code length. Therefore, the pulse train will be sufficiently repeated within the 100 ms, as shown in Fig. 3. In this study, k was chosen to vary from 7, 9, 11 to 13, in order to evaluate the impact of code length on the radar performance. Allocation of different MLSs to different radars facilitates the suppression of interference from other radars, if the respective MLSs have good cross-correlation properties. To achieve this condition, MLS feedback taps generating preferred pairs of MLS were selected and assigned to each
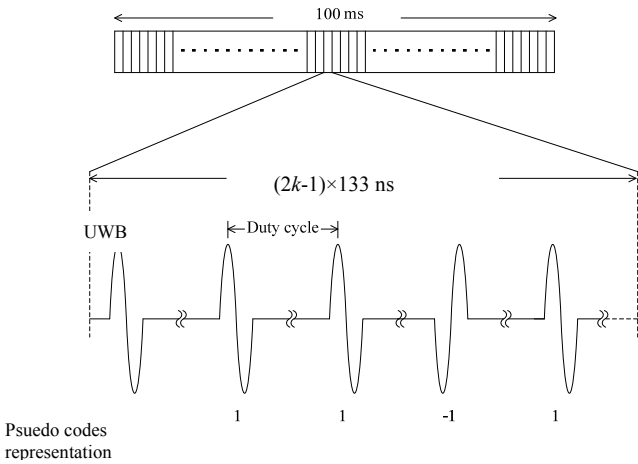
Fig. 3. Example of a BPSK-modulated pulse train with an MLS.

Order of MLS code, k	MLS feedback taps (MLS1)	MLS feedback taps (MLS2)
7	(3, 7)	(1, 2, 3, 7)
9	(4, 9)	(3, 4, 6, 9)
11	(2, 5, 8, 11)	(2, 3, 10, 11)
13	(1, 3, 4, 13)	(4, 5, 7, 9, 10, 13)

Tab. 1. Selected MLS feedback taps to generate preferred pairs of MLS.

each radar, as listed in Tab. 1. The total number N of the preferred pairs of MLSs, however, is limited: e.g. $N = 6$, 2, 4, and 4 when $k = 7$, 9, 11, and 13, respectively. An MLS yields a two-level autocorrelation function:

$$\theta(\tau) = \begin{cases} 2^k - 1 & \text{if } \tau = 0 \\ -1 & \text{if } \tau \neq 0. \end{cases} \quad (5)$$

and a preferred pair of MLSs possesses a relatively low level cross correlation function. On the other hand, GSs possess no particular preferred pairs. GSs possess $(2k - 1)$ different sequences. GSs provide relatively low three-level cross correlation function ($2^{(k+1)/2} - 1$, -1, and $-2^{(k+1)/2} - 1$). The autocorrelation function of the GSs of a length of k is given by

$$\theta(\tau) = \begin{cases} 2^k - 1 & \text{if } \tau = 0 \\ \text{either} \quad 2^{(k+1)/2} - 1, -1, \text{or} -2^{(k+1)/2} - 1 & \text{if } \tau \neq 0. \end{cases} \quad (6)$$

The larger fluctuating $\theta(\tau)$ (when $\tau \neq 0$) is a drawback of the GSs. Accordingly, auto correlation and cross correlation of GS is slightly inferior to it of MLS. However, GS possess far more different sequences. Therefore, utilization of GS can suppress interference from multiple other radars. On the other hand, in either case of random sequence, the selection of k and feedback taps should be negotiated among the cars beforehand, for instance, via an inter-vehicle communication link. The design of physical layer and communication protocol for this purpose is not studied within this paper, since it is outside the scope of the present study.

3.2 Simulation Structure

A series of numerical simulation was carried out to evaluate the probability of false alarm (P_{fa}) and probability of detection (P_d) of the UWB radar system. Signal flow diagrams and representative waveforms are presented in Fig. 4. Figure 4(a) depicts a case that the receiver receives the desired signal alone, generated from a unique code designated by either MLS1 or GS1. Additive white Gaussian noise (AWGN) was injected into the signal at the receiver input port. Signal-to-noise power ratio (SNR) was fixed at 10 dB. For the sake of presentation clarity, the matched filter output was normalized by the maximum value of auto-correlation function ($2k - 1$ for a k-stage MLS and GS), as shown in Fig. 4(a). Figure 4(b) depicted the case where the undesired signal U alone entered the receiver, in which P_{fa} was calculated by varying the DUR and threshold level. Figure 4(c) represents the signal flow and the waveforms when both the desired and undesired signals co-exist within the same channel. The P_d was calculated under the presence of undesired signal U in the system, when P_{fa} was fixed 10^{-2} or 10^{-4} for DUR between -10 to 30 dB, and the length of sequences $L = 127$, 511, 2047, 8191 (corresponding to $k = 7$, 9, 11, and 13, respectively). The maximum antenna gain, obtained from product of transmission and reception was assumed to be 11 dBi, and the half-power beamwidth is 60° (common value for typical slot antennas).

The simulation was carried out based on the following conditions:

- Matched filter output was normalized by the maximum value of autocorrelation function in Fig. 4(a).

- The same normalization was applied to the matched filter output in Figs. 4(b) and (c).

- The P_{fa} was calculated by varying DUR and the threshold level in Fig. 4(b).

- The P_d was calculated when P_{fa} was fixed at 10^{-2} or 10^{-4}.

4. Simulation Results

First, the false alarm probability P_{fa} was calculated when no target is present in the system, and the receiver receives only the undesired signal U generated by MLS2 or GS2 from the interfering radar. The matched filter output in Fig. 4(a) was normalized for a certain level of the desired signal D by the maximum value ($2k - 1$) of auto-correlation function of MLS1 and GS1. Similarly, the matched filter output in Fig. 4(b) was normalized in a similar manner, where the U was varied at a ratio between -30 to 10 dB ($-10 \leq DUR$ [dB] ≤ 30) to the desired signal level D. The calculated P_{fa} for $L = 127$, 511, 2047, 8191 (corresponding to $k = 7$, 9, 11, and 13, respectively), are plotted
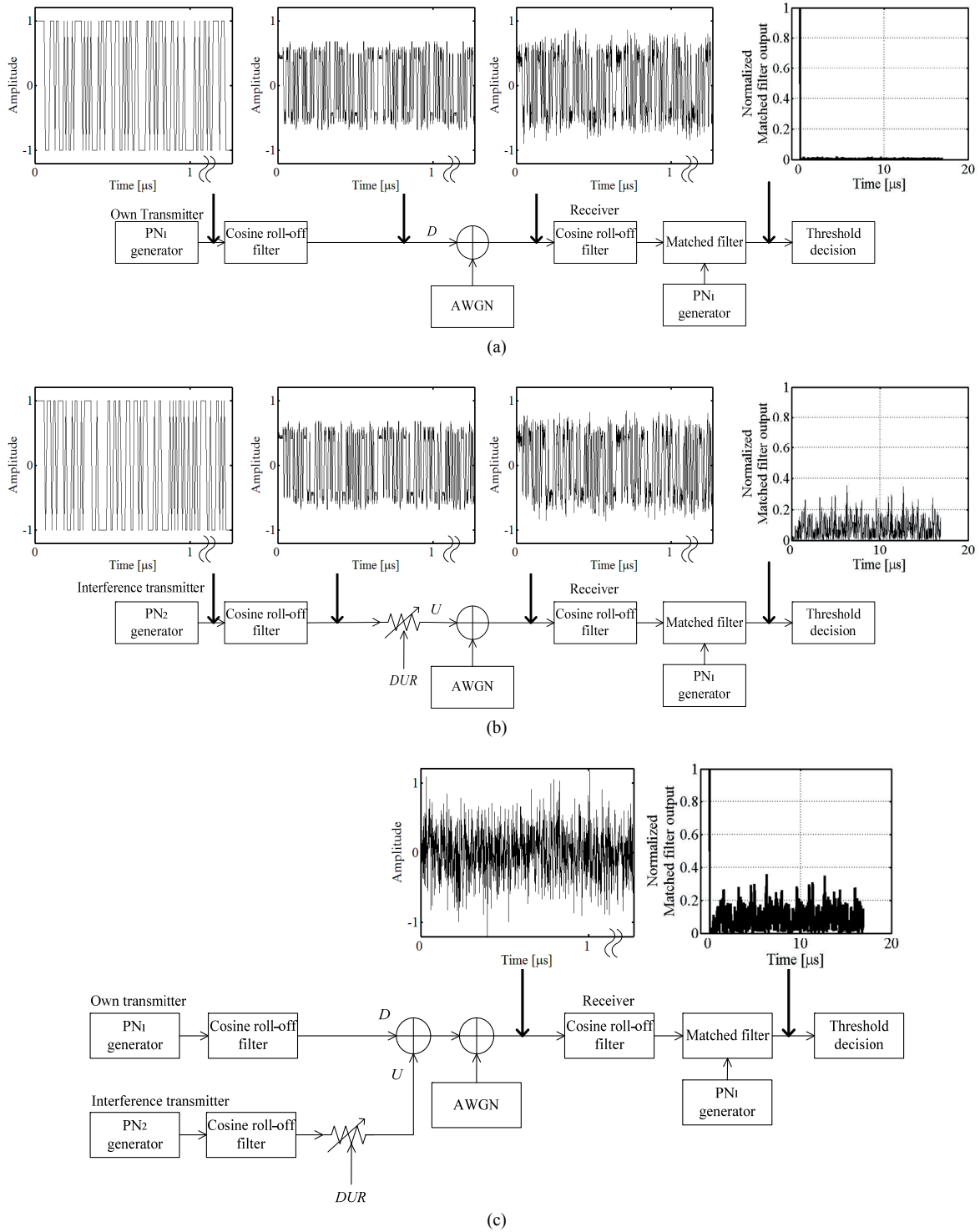
Fig. 4. Block diagrams and simulated waveforms used in the study. The receiver receives: (a) the desired signal from host vehicle radar transmitter, (b) the undesired signal from the other radar transmitter, or (c) the desired and the undesired signals simultaneously.

in Figs. 5 and 6 between $-10 \leq DUR \leq 10$ dB. It can be observed from the figure that higher DUR contributes to decrease in P_{fa} yielding the same threshold level. It was also found that larger k results in the lower threshold level yielding the same P_{fa}. The P_{fa} was almost the same when comparing MLS and GS. It is considered that an effect of low three-level cross correlation was lost because AWGN was super-imposed to the signal at the receiver input.

Probability of detection for both cases of MLS and GS were calculated by using the threshold level when both desired and undesired signals existed at $-10 \leq DUR \leq 30$ dB. Figures 7 and 8 show the simulation results of P_d when $P_{fa} = 10^{-2}$ and 10^{-4}. The MLS and GS modulation resulted in significant improvement of P_d in comparison with no use of MLS and GS. For the case of MLS, improvements relative to no use of MLS were approximately
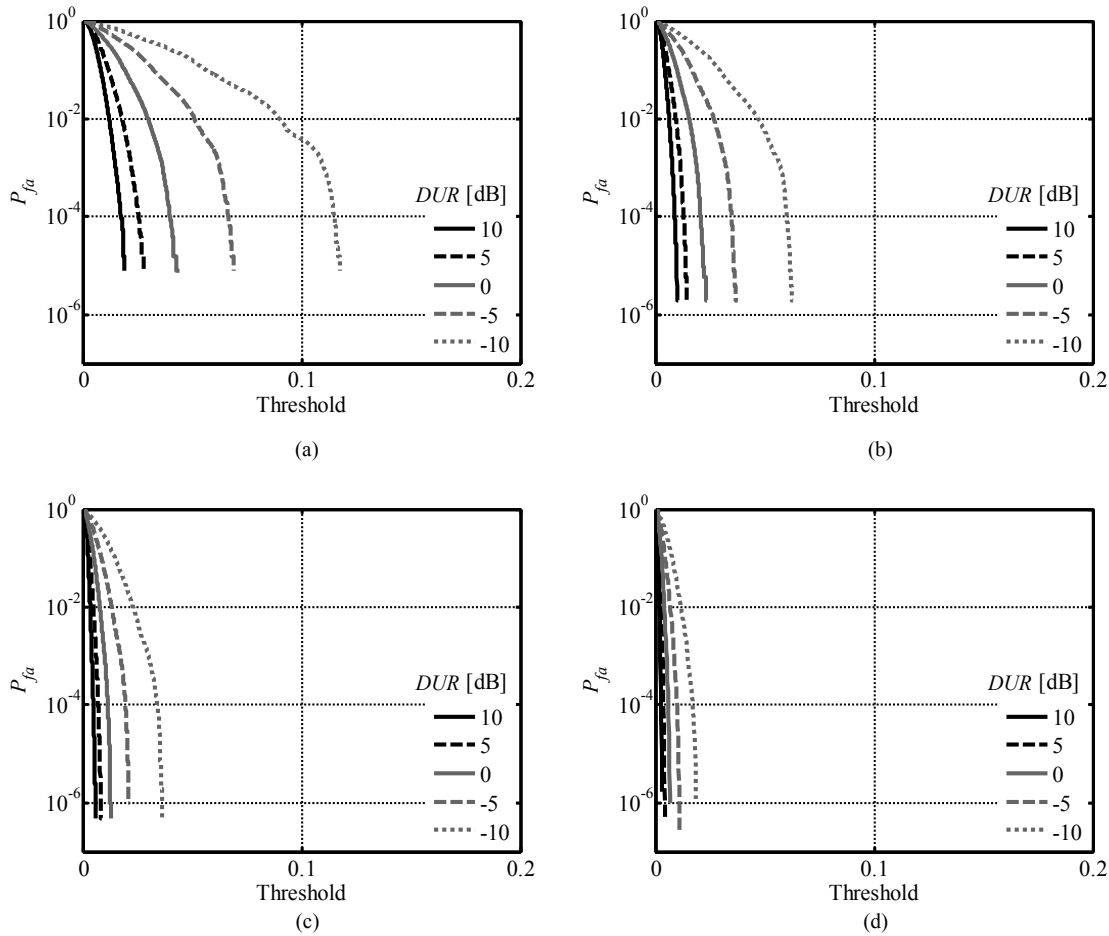
Fig. 5. Simulated false alarm probability: length of MLS = (a) 127, (b) 511, (c) 2047, and (d) 8191.

21, 27, 33, and 39 dB for L = 127, 511, 2047, 8191, respectively. This is because the maximum values of auto-correlation function of MLS are 127 (21 dB), 511 (27 dB), 2047 (33 dB), and 8191 (39 dB) for L = 127, 511, 2047, 8191, respectively. Addition of the order of MLS stages k by 2 induced approximately 5 dB reduction of DUR yielding the same level of P_d.

Improvements relative to no use of GS were approximately 23, 27, 33, and 40 dB for L = 127, 511, 2047, 8191, respectively, as plotted in Fig. 8. Similar to the case of MLS, improvement of approximately 5 dB of P_d was observed by increasing the length of the GS codes. Figure 9 compares both the P_d of MLS and GS. The detection probabilities were found almost the same for MLS and GS, the former of which yielded slightly higher performances, as typically summarized in Tab. 2. The performance improvement marked by usage of GS was larger when the DUR was smaller (for example DUR = −10 dB). This fact is in parallel with the previous studies of comparisons between MLS and GS in bit error rate and peak-to-noise ratio in the fields of spread spectrum communication [9] and radar [10], respectively.

5. Conclusion

This paper presented a quantitative evaluation of the performance of radars employing pseudo random sequences -MLS and GS, for suppressing interference from nearby radars. The study was carried out through numerical simulations that were constructed based on a link budget considering a scenario where two cars equipped with independently operating UWB radar pass each other on a road. Assuming important parameters for the scenario such as 45°-inclined polarization and distance d between the two passing cars, DUR was found to vary approximately from −10 to 30 dB. The UWB radar under consideration transmits a UWB pulse train that is modulated by BPSK with

DUR[dB]	P_{fa}	MLS	GS
30	10^{-2}	0.999	0.999
	10^{-4}	0.999	0.999
10	10^{-2}	0.995	0.995
	10^{-4}	0.993	0.993
-10	10^{-2}	0.963	0.963
	10^{-4}	0.946	0.945

Tab. 2. Typical detection probability: length of MLS and GS = 8191.

either MLS or GS to suppress interference from the radar of the other passing car. Allocation of different MLSs and GSs to different radars facilitates the suppression of interference from other radars. Threshold level was determined to yield false alarm rates of either at 10^{-2} or 10^{-4} (caused by interference from the other radar) when no return signal was received from its own radar transmitter. The employment of MLS or GS to modulate the radar pulse train resulted in significant improvement in detection probability. Improvements relative to no use of MLS were approxi-

mately 21, 27, 33, and 39 dB for L = 127, 511, 2047, 8191, respectively. Improvements relative to no use of GS were approximately 23, 27, 33, and 40 dB for L = 127, 511, 2047, 8191, respectively. The detection probabilities were found almost the same between MLS and GS. These results show that GS is comparable to MLS when applied to the spread-spectrum vehicular radars, however it is more advantageous considering the larger number of available sequences. Both MLS and GS marked improvements of P_d with increasing code length.
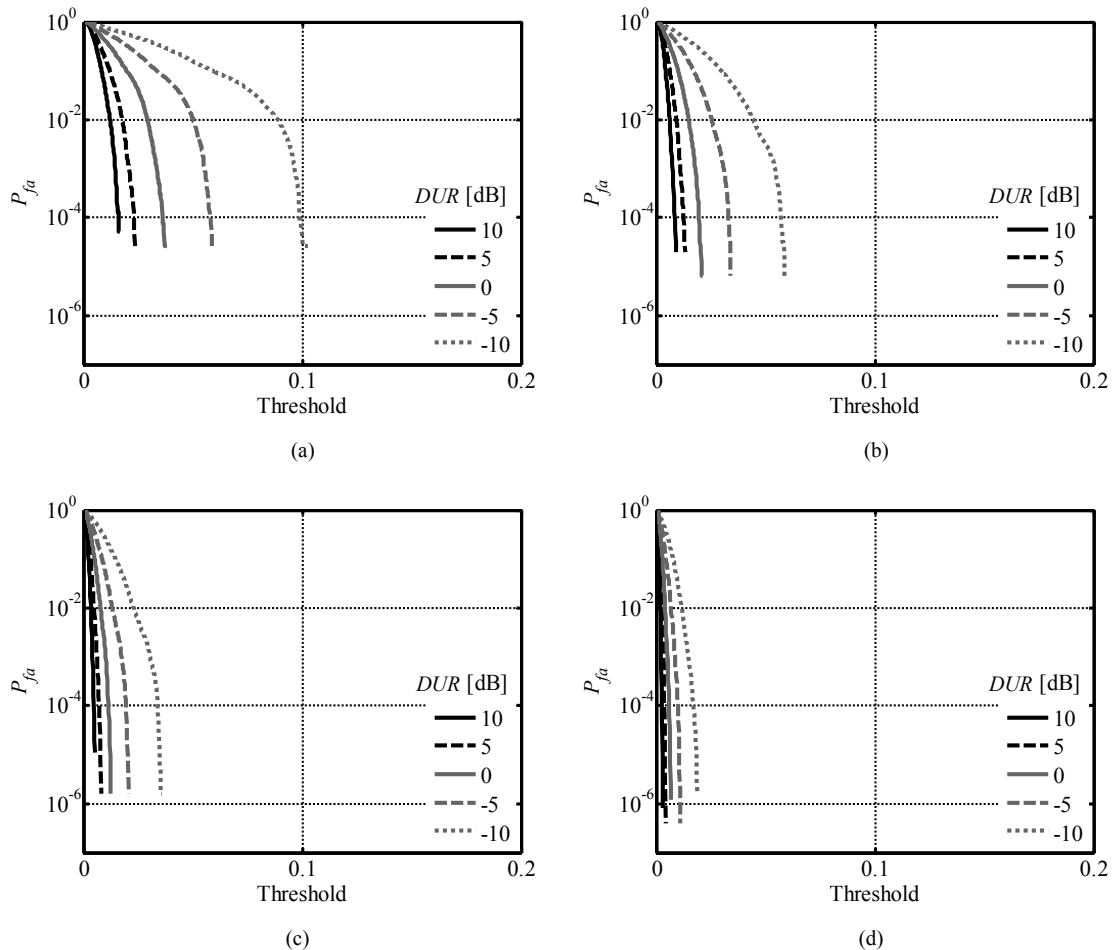

(a)

(b)

(c)

(d)

Fig. 6. Simulated false alarm probability: length of GS = (a) 127, (b) 511, (c) 2047, and (d) 8191.
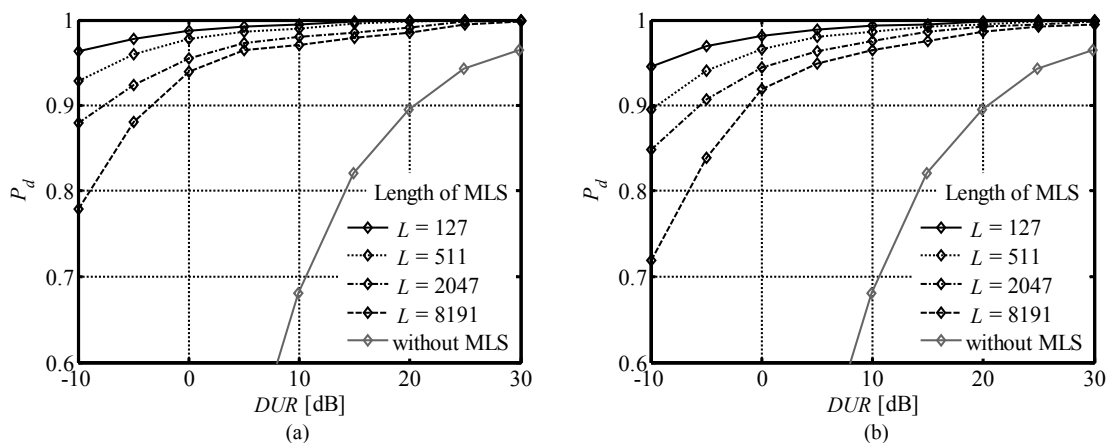

(a)

(b)

Fig. 7. Simulated detection probability of MLS: when P_{fa} = (a) 10^{-2} and (b) 10^{-4}.
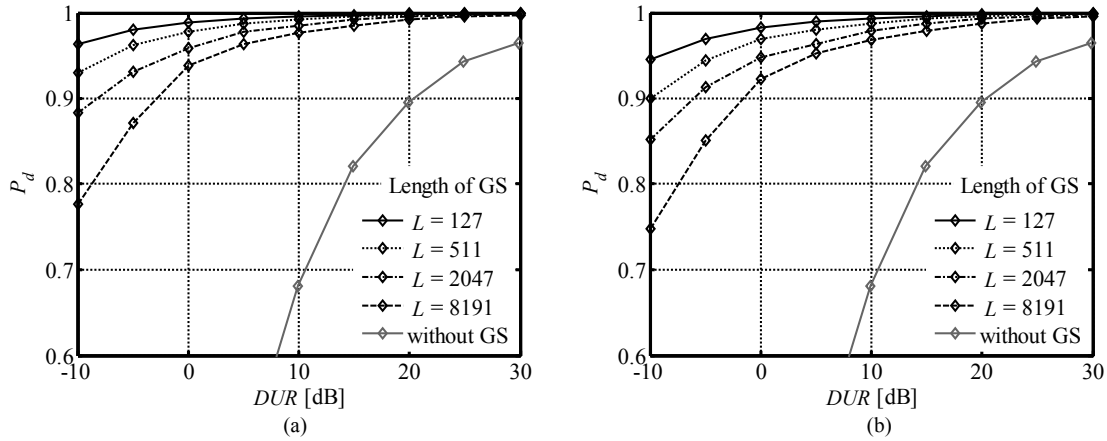
Fig. 8. Simulated detection probability of GS: when P_{fa} = (a) 10^{-2} and (b) 10^{-4}.
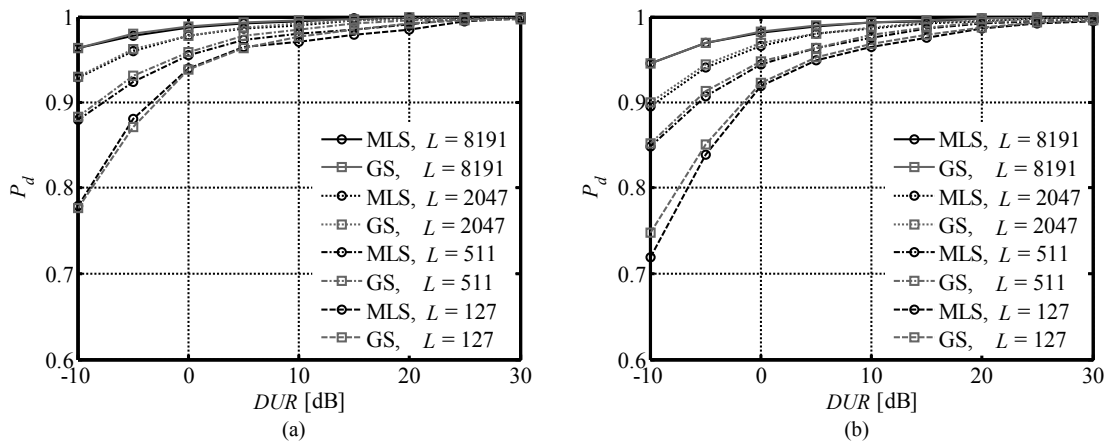

Fig. 9. Comparison of P_d between MLS and GS: when P_{fa} = (a) 10^{-2} and (b) 10^{-4}.

Appendix

The first Fresnel zone radius when operating the UWB radar at 25 GHz of center frequency. The nth-Fresnel zone radius can be calculated using the following equation,

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \qquad (7)$$

where d_1 and d_2 is the distance from the transmitting and receiving antennas to the center of the Fresnel zone, λ is the wavelength, and n is the index number for the nth-Fresnel zone radius. Assuming the distance 10 m, d_1 and d_2 are both 5 m. Centre frequency of 25 GHz gives us λ = 12 mm, hence, F_1 = 0.17 m. The transmitting and receiving antennas heights of 0.5 m are sufficient for the system to exclude a destructive reflected wave from the ground that could reduce the receiving power.

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