Consideration Of LFM Signal For Co-Channel Multisite Radars

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Abstract

As one of solutions to obtain efficient use of spectrum, we suggest a methodology for the co-channel multi-site radar operations based on a shifted linear frequency modulation (SLFM) signals. From the cross-correlation characteristics among SLFM signals, we find a candidate set of SLFM signals with the minimum acceptable level of the correlation. To verify the proposed algorithm, numerical analysis has been performed for several radars operating at the same channel, and distances and range profiles are also examined for interference and noise including the effect of starting time error of SLFM signals.

Keywords: *Linear FM, cross-correlation, interference, radar, co-channel operation.*

1. Introduction

In generalradar frequency bands are independently assigned to avoid interference from unwanted signals of spurious or harmonics, and also from the operational point of view, the spatially proper arrangement of radars is possible to decouple interference even though they are operated at the multi-site co-channel band [1-3]. The practical basis for signal orthogonality lies in the time and/or frequency structure of the signals in the set, and in its most simple form occurs as either time-division or frequency-division multiplexing [4].

However the radio spectrum is a vital but limited natural resource which provides the means to convey audio, video or other information content over distances [5]. Recently due to the explosive demand for mobile communication service, the effective use of spectrum has been greatly issued, especially for the VHF and UHF bands. To achieve such a goal if compatibility is assured between wireless systems, it can only be used optimally in the same or adjacent frequency bands [6].

On the other hand, it is well known that the basic methodologies for pursuing the efficient spectrum usage should adopt co-channel multi-site operations without any restrictions. However in order to achieve these, first of all the orthogonal property among a candidate set of signals should be mathematically maintained [7-10]. Then highly efficient spectrum management can be realized by deploying co-channel multi-site systems if some restrictions on practical implementation are resolved.

The basic concept of efficient spectrum usage is illustrated in Fig. 1 for meteorological radar bands. As seen in the lower part of Fig. 1, to acquire spectrum resource needed for the future mobile communication service or others, if possible, the total bandwidth for meteorological radars should be reduced as minimum as possible, by adopting co-channel multi-site operations so long as the signals with orthogonal property are used.
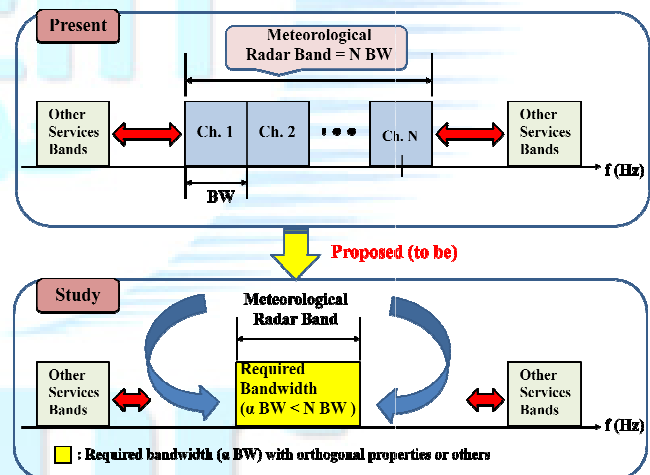

Fig. 1 Concept for efficient spectrum use in meteorological radar bands.

In this paper as one of solutions to obtain efficient use of spectrum, we suggest a methodology for the co-channel multi-site radar operations based on a shifted linear frequency modulation (SLFM). From the cross-correlation characteristics among SLFM signals, we find a candidate set of SLFM signals with the minimum acceptable level of the correlation [11]. To verify the proposed algorithm, numerical analysis has been accomplished for several radars operating at the co-channel and its results are also examined under interference and noise including the effect of starting time error of SLFM signals.

2. Shifted LFM signal and orthogonality

2.1 Radar system with LFM signals

Fig. 2 shows a simplified block diagram of the radar with LFM signal. The instantaneous frequency of an RF carrier is linearly deviated by bandwidth B during a period T. The signals transmitted and received from a point object at range R are given, respectively, by

$$S_t(t) = A_t \Pi\left(\frac{t}{T}\right) \sin\left(2\pi f_1 t + \frac{\pi B t^2}{T}\right) \qquad (1)$$

$$S_r(t) = A_r \Pi\left(\frac{t-\tau}{T}\right) \sin\left(2\pi f_1 (t - \tau) + \frac{\pi B (t-\tau)^2}{T}\right) \qquad (2)$$

where A_t and A_r are the amplitudes of transmitted and received signals, respectively, Π denotes a rectangular function and $\tau (= 2R/c)$ is a round trip time to distance R of a point target, and f_1 is the starting frequency of LFM signal.

Regarding parameters of the intended application, $T \gg 2R/c$, that is, the signal duration greatly exceeds the round-trip time of echo signal. Then the output of the mixer can be properly approximated by

$$S_o(t) = A_o \Pi\left(\frac{t}{T}\right) \cos\left[\left(\frac{4\pi B R}{cT}\right) t + 2\pi f_1 \frac{2R}{c}\right] \qquad (3)$$

Since the signal frequency of Eq. (3) is proportional to range R, Fourier analysis of the mixer output signal provides a measure of range. The second term in the cosine argument of Eq. (3) is phase angle proportional to R and the carrier frequency.
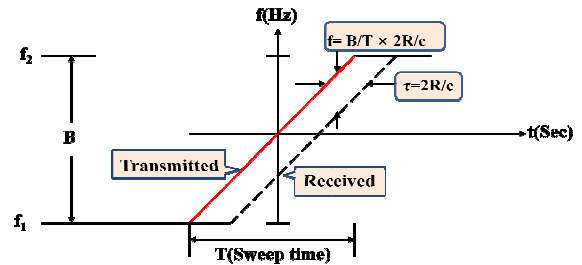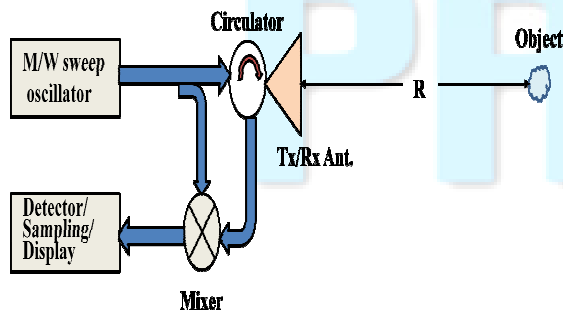

Fig. 2 A simplified geometry of the radar with LFM signals.

2.2 Signal orthogonality

Now let's consider a sort of waveforms as a candidate set of signals in a radar system. Two signals of $S_m(t)$ and $S_n(t)$ are said to be rigorously orthogonal if

$$1/T \int_0^T S_m(t) S_n^*(t) dt = \begin{cases} 1, & n = m \\ 0, & n \neq m \end{cases} \qquad (4)$$

where T is a integrating period of signal and $*$ denotes the complex conjugates.

The practical basis for signal orthogonality exists on the time and/or frequency structure of the signals in the set. However from the Fourier transform implications to any useful set of signals, rigorous orthogonality among signals in Eq. (4) can not be practically realized. So a less strict definition of orthogonality is given by

$$\left| 1/T \int_0^T S_m(t) S_n^*(t) dt \right| < \varepsilon, \ n \neq m \qquad (5)$$

where ε is a measure of some acceptable level of cross-correlation or interference between $S_m(t)$ and $S_n(t)$.

For instance Fig. 3 shows the auto-correlation function of the LFM signals.
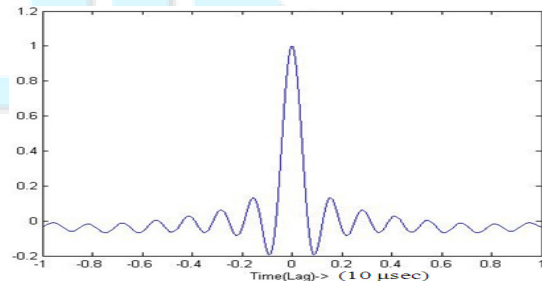

Fig. 3 Auto-correlation function of the LFM signals.

2.3 Interoperable time-shifted signal selection algorithm

Let $s(t)(0 \leq t \leq T)$ be a given signal with sampling time $0 = t_0 < t_1 < t_2 < \cdots < t_n = T$ and N be the number of radars that are assigned a time-shift signal for each [11].

Step 1: Uncorrelated signal selection.

First, we find the time-shifted signals $s(t; t_i)$ that are uncorrelated with the original signal $s(t)$. Given a constant time t_i, the time-shifted signal is defined by

$$s(t; t_i) = \begin{cases} s(t + t_i), & 0 \leq t \leq T - t_i \\ s(t + t_i - T), & T - t_i < t \leq T \end{cases} \quad (6)$$

Then we want to select the signal $s(t; t_i)$ or a constant t_i satisfying

$$|corr(s(t), s(t; t_i))| = \left| \int_0^T s(t)s(t; t_i)dt \right| < \varepsilon \quad (7)$$

for some small positive number ε. The threshold value ε is determined in experiments, depending on the system parameters. We call t_i as the shift time of the signal $s(t; t_i)$.

Step 2: Interoperability assurance test.

For each selected time-shifted signal by step 1, we do two interoperability tests with the original signal $s(t)$ as follows. Let $s(t; t_i)$ be a time-shifted signal selected by step 1. First, we assume that $s(t)$ and $s(t; t_i)$ are the signals of the reference and interference radars, respectively. Then check if their mixed output signal has only one peak and low side lobe. Otherwise, we discard the signal $s(t; t_i)$. Second, changing the roles of $s(t; t_i)$ and $s(t)$, check if their mixed output signal has only one peak and low side lobe. Otherwise, we discard the signal $s(t; t_i)$.

Step 3: Selection of N time-shifted signals with minimum correlation.

Let Q be the set containing all N combinations of the shift times of the candidate time-shifted signals selected by step 1 and 2. Then, N interoperable time-shifted signals C_N can be found by

$$C_N = \text{argmin}_{C \in Q} \left(\max_{t_i, t_j \in C} |corr(s(t), s(t; t_i))| \right) \quad (8)$$

This choice is based on the fact that the uncorrelated signals, in general, do not interfere each other.

3. Simulated results and discussions

3.1 Radar geometry and system parameters

To show some computational results the time-shifted LFM signals are selected based on satisfying the criterion on the minimum cross-correlation among a lot of TSLFM signals. Considering the target identification of a single point object, 5 radars are assumed to be simultaneously operated under the same channel with the synchronized GPS clock as shown in Fig. 4. 4 radars have time-shifted LFM signals in comparison to the original LFM signal, which was found by numerical computation from the suggested algorithm.
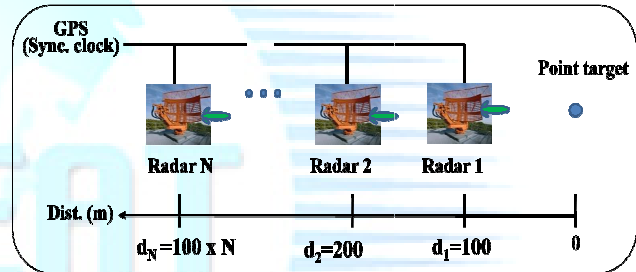

Fig. 4 Multi-site radars operating by TSLFM signals under co-channel.

The target reflectivity is assumed to be 1.0 with an isotropic direction, and the signal loss due to round-trip distance was neglected. In addition, the transmitted and reflected signals are transparent to all radars during they propagate in the forward or backward direction, but each radar receives the reflected signal from its own transmitted one as well as interferences from the other radars. For convenience, radar parameters of multi-site co-channel operation are chosen like Table 1.

Table 1: Assumed radar parameters

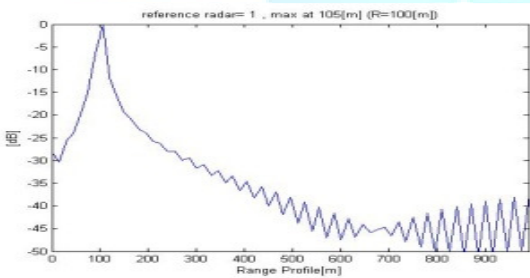| Parameters	Values
Bandwidth B	10 MHz
Sweep time T	0.01 s
Signal slope B/T	10^9 Hz^2
Start frequency f_1	2.9 GHz
f_{max} (for R_{max} = 1km)	6.6667x10^{3}Hz
Sampling rate f_s	$\geq 2f_{max}$ Hz

3.2 Simulated results

First, consider the target identification of a single point object for the noiseless case. The simulated results are summarized in Table 2 and Fig. 5. Since 5 radars are operated at the co-channel band, the reflected signal of the

concerned radar is interfered with the remainder. For instance, assuming radar 1 to be the concerned radar, unwanted signals or interferences from the other radars will affect the radar 1. Hence detected target distances from radar 1 will be calculated as 150, 200, 250, 300 m for those interference signals arising from radar 2 to radar 5, respectively, which indicates the averaging round-trip distance from interferer to the target and target to radar 1. Therefore the Fast Fourier Transform (FFT) of received signal at the radar 1 illustrates the multiple peaks in the frequency domain caused by interference effect.

The range profiles are constructed as shown in Fig. 5. From the detected target distances, it is interesting to note that all radars are possible to retrieve the target distance closely within tolerable error of one range resolution, even though 5 radars utilize the same LFM signals with different starting frequencies at co-channel band.
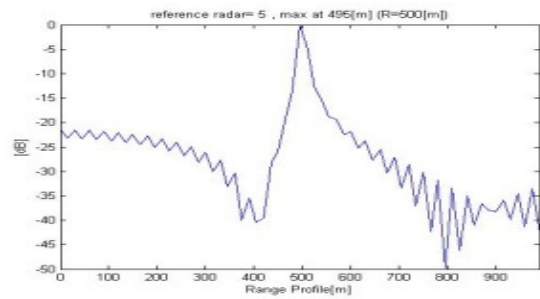
Table 2: Detected distances without noise

| Object Dist.	Detect. Dist.	Interferer	Results
100 m	105 m	Radar 2,3,4,5	Fig. 5(a)
200 m	195 m	Radar 1,3,4,5	
300 m	300 m	Radar 1,2,4,5	Fig. 5(b)
400 m	405 m	Radar 1,2,3,5	
500 m	495 m	Radar 1,2,3,4	Fig. 5(c)
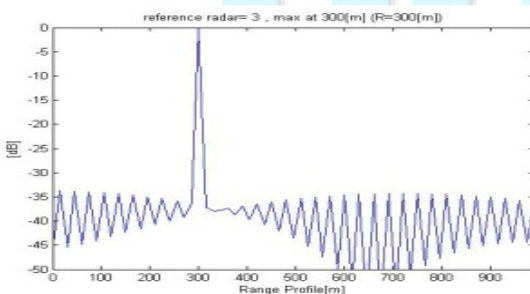
(c) Radar 5

Fig. 5 Range profiles.

Next, to investigate the multi-target effect under AWGN using the same SLFM signals previously, the simulation results for two point targets are summarized in Table 3 with S/N = -3 dB. S/N was defined as the ratio of variance of LFM signal to variance of noise. Reconstructed range profiles are shown in Fig. 6, where the peak values are equivalent to detected target distances with allowable error of range resolution. From these results, it can be noted that the suggested method can be applied to the detection of target distance such as altimeters operating at co-channel multi-sites.

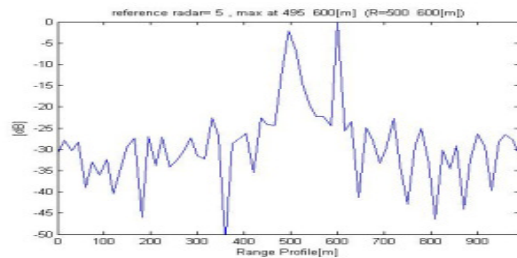Table 3: Simulated results for two point targets (S/N=-3.0dB)

Object Dist.	Detect. Dist.	Interferers	Results
100, 200 m	105, 195 m	Radar 2~5	Fig. 6(a)
200, 300 m	195, 300 m	Radar 1,3~5	
300, 400 m	300, 405 m	Radar 1,2,4,5	Fig. 6(b)
400, 500 m	405, 495 m	Radar 1~3,5	
500, 600 m	495, 600 m	Radar 1~4	Fig. 6(c)
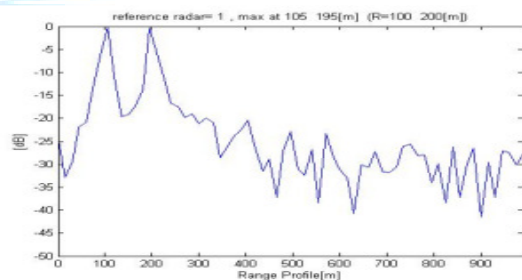
(a) Radar 1

(b) Radar 3

(a) Radar 1
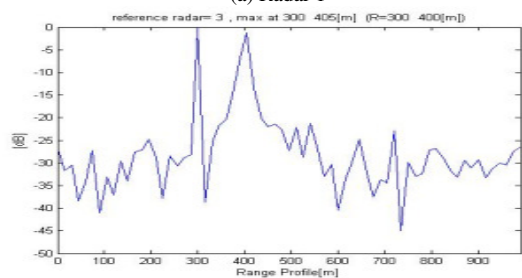
(b) Radar 3

(c) Radar 5

Fig. 6 Range profiles.

On the other hand, in order to check the limitation of this SLFM methodology in view of how many radars can be operated at co-channel band, simulated results are summarized in Table 4 for a point target without noise.

From simulated results it was confirmed that target distance can be clearly detected for the number of radar up to 7. However to increase the number of radar operating at co-channel band, it is necessary to seek more powerful algorithm to select SLFM signals which leads to the minimum interference among these signals.

Table 4:Simulated results for a point target without noise

| Object Dist.	Detect. Dist.	Interferers
100 m	105 m	Radar 2~7
200 m	195 m	Radar 1, 3 ~ 7
300 m	300 m	Radar 1,2,4~7
400 m	405 m	Radar 1~3,5~7
500 m	495 m	Radar 1~4, 6,7
600 m	600 m	Radar 1~5, 7
700 m	705 m	Radar 1~6

Finally let's examine the effect of time error of GPS clock used for multi-site radar operations. To have the exact starting time of SLFM signals are essential for synchronizing co-channel multi-site operations. So the percentage time error of GPS clock is defined by $\Delta(\%) = |\varepsilon|/T$ where ε means the time difference from the predefined time of SLFM signal and T denotes the period of LFM signal. Fig. 7 and Table 5 represent the detected distances and range profiles of corresponding radar for the time error of 5 % for 4 multi-site radars.

Table 5: Detected distances for time error of GPS clock

Δ(%)	Actual/Detected Dist.			
	Radar 1	Radar 2	Radar 3	Radar 4
0	100/105	200/195	300/300	400/405
1	100/120	200/210	300/300	400/405
2	100/120	200/210	300/300	400/420
3	100/120	200/195	300/300	400/405
4	100/120	200/195	300/300	400/405
5	100/105	200/210	300/300	400/420
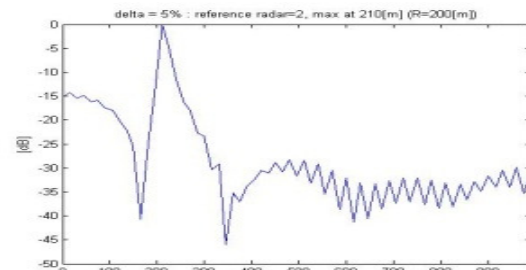
(a) Radar 2
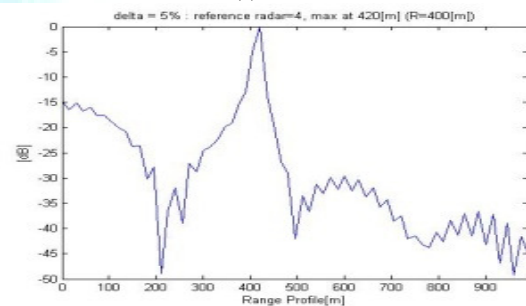
(b) Radar 4

Fig. 7 Range profiles.

4. Conclusions

Based upon the minimum correlation of the shifted linear frequency modulation (SLFM) signals with the same bandwidth and different starting frequencies, we proposed the methodology of co-channel multi-site radar operations in conjunction with GPS clock. For the given LFM signal, the proper algorithm for selecting SLFM signals are suggested for obtaining some acceptable level of cross-correlation or interference.

In order to verify the proposed methodology, for the given system parameters numerical analysis was performed for multi-point targets as a function of noise and time error of GPS clock. From computational results, it was shown that the suggested methodology can be applied to an altimeter for detecting target distance and its results have a good agreement with actual distances with allowable resolution errors. As further works Doppler effect of a moving target will be studied for sawtooth and triangular LFM signals.

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