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A Multi-Channel Correlative Vector Direction Finding System Using Active Dipole Antenna Array for Mobile Direction Finding Applications

Jun-Ho Choi · Cheol-Sun Park · Sun-Phil Nah · Won Jang

Abstract

A fast correlative vector direction finding(CVDF) system using active dipole antenna array for mobile direction finding(DF) applications is presented. To develop the CVDF system, the main elements such as active dipole antenna, multi-channel direction finder, and search receiver are designed and analyzed. The active antenna is designed as composite structure to improve the filed strength sensitivity over the wide frequency range, and the multi-channel direction finder and search receiver are designed using DDS-based PLL with settling time of below 35 *us* to achieve short signal processing time. This system provides the capabilities of the high DF sensitivity over the wide frequency range and allows for high probability of intercept and accurate angle of arrival(AOA) estimation for agile signals. The design and performance analysis according to the external noise and modulation schemes of the CVDF system with five-element circular array are presented in detail.

Key words : Correlative Vector Direction Finding(CVDF), Direction Finding(DF), Direct Digital Synthesizer(DDS).

Ⅰ. Introduction

A direction finding system is ever increasing in importance for various applications such as radio frequency monitoring, electronic support(ES), electronic intelligence(ELINT) and also location based service(LBS). Many of DF techniques are described and studied to correctly compute the AOA from the transmitted signal sources such as Watson-Watt[1], interferometer[2], correlative interferometer[3] and super-resolution technique (e.g. multiple signal classification(MUSIC))[4]. Although they provide resonable performances, the CVDF technique is preferred to the mobile DF system at communication-band because it has short processing time and high DF accuracy. In mobile scenarios, the CVDF system can be implemented by multi-channel, dual-channel or single-channel receiver. In comparison with dual- and multi-channel CVDF system, the single-channel CVDF system is low cost and compact structure, but it has the complexity of pre-processing circuitry and time consuming to estimate the AOA of the signal of interest[5],[6]. These properties are impractical to estimate AOA of short duration signals like frequency hopping spread spectrum(FHSS) because the processing time has to be less than several tens *ms*. So, the multi-channel CVDF system is useful for fast direction finding applications.

The main elements of the multi-channel CVDF system are antenna array, multi-channel direction finder and digital search receiver. They have to be carefully designed because the performance of the CVDF system is dependent on their design parameters which are gain, radiation pattern and array geometry of antenna, and tuning-speed and sensitivity of the direction finder and search receiver. In particular, for mobile electronic warfare (EW) applications, the DF system is mainly required the capabilities of high speed processing, high accuracy and sensitivity, and bandwidth flexibility to handle diverse signal types.

In this work, we investigate the main elements of the multi-channel CVDF system such as a low noise broadband active composite dipole antenna and fast tunable receiver to improve the DF sensitivity and processing time, respectively. The active antenna is designed as composite structure which consists of the long dipole and short dipole to improve the gain over the wide frequency range. This type of antenna plays a role in two dipole functionally and also one dipole physically[7]. The multi-channel direction finder is designed using the DDS-based PLL with setling time of below 35 *us* to obtain high scanning speed and probability of intercept. The search receiver is designed as digital-IF FFT receiver which has characteristics of variable bandwidth and resolution, and fast scanning speed. We also describe the implementation of the five-channel CVDF system with the circular geometry of the five active dipole antennas and analyze the limitation of the performance

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according to the external noise sources and modulation schemes.

Ⅱ. Design and Configuration of the Five-channel CVDF System

As shown in Fig. 1, the CVDF system is composed of antenna array, multi-channel direction finder, digital search receiver, and display/control unit. The five electrically short vertical active dipole antennas are placed in an equilateral circle to reduce the mutual coupling between antennas and supporting mast. The wideband input signal fed by circular antenna array simultaneously provides with five-channel direction finder and digital search receiver. The digital search receiver plays a role in fast monitoring the interesting signals with short duration in dense signal environment and also provides the frequency and amplitude data of the interesting signals with the direction finder to calculate the AOA. The display/control unit provides the graphical display of the DF results as well as user control of system operation.

2-1 Low Noise Active Composite Dipole Antenna

The DF antenna in the field of communications, radio-monitoring and radio-location has to be designed as a large bandwidth, wide dynamic range, excellent field sensitivity and small dimension to provide optimum signal receptions at the limited dimension[2],[8]. To satisfy these requirements, the active antenna is designed as composite structure of passive radiator as shown in Fig. 2. The passive radiator is composed of the long, short dipole and inner wire which provides the separation both of them. At low frequencies, the antenna operates as long dipole and at high frequencies, the short dipole is active. The design parameters are defined as total dipole length *Lt*, short dipole length *Ls*, thin wire gap *Gw* and dipole diameter ϕ. The total length of composite dipole is restricted by 1 m to reduce the size and weight. The large impedance change resulting from shortening radiator is compensated by applying the terminal of radiator directly to an active component with very high impedance that act as an impedance converter and often as an amplifier, too. The active circuit is composed of two cascade amplification circuits with total

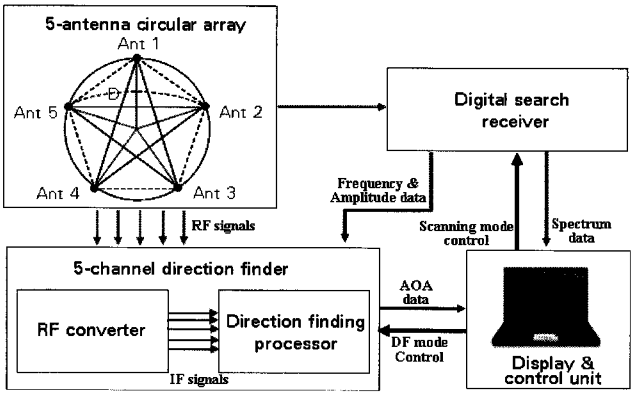


Fig. 1. System diagram of the five-channel CVDF system.

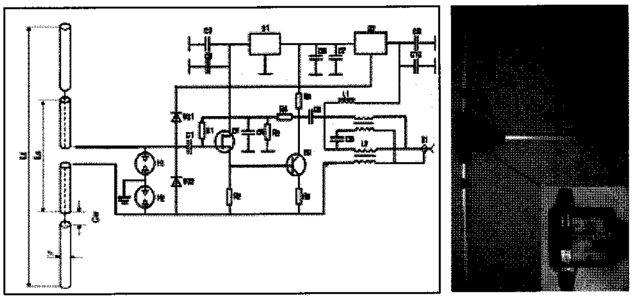

(a) (b)

Fig. 2. (a) Configuration and (b) implementation of the active composite dipole antenna.

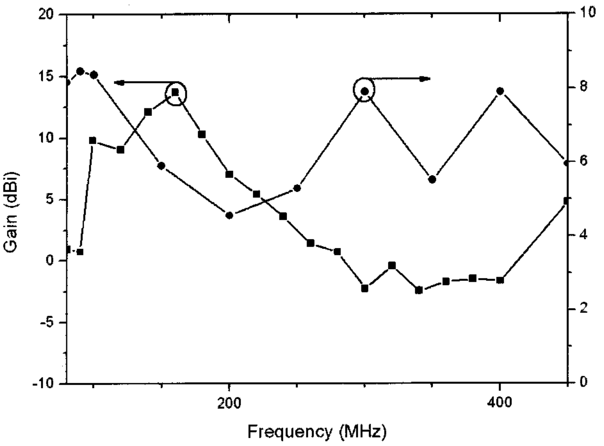


Fig. 3. Measured gain and noise figure.

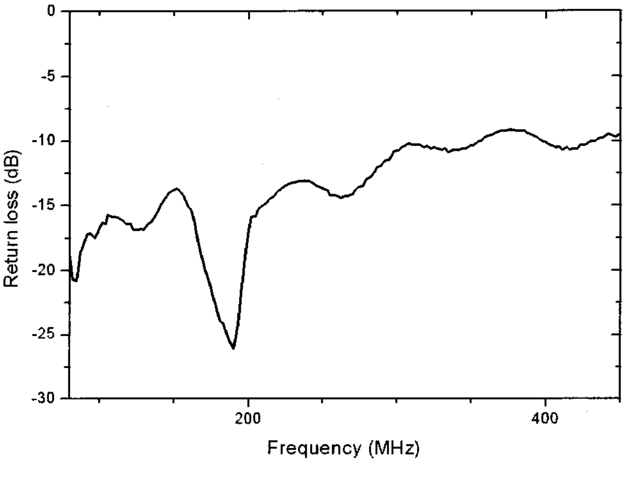


Fig. 4. Measured return loss.

transfer constant of +5.5 dB at the 50 Ohm load. The first amplifier stage(Q1) is FET source follower amplifier which gives high input impedance to antenna element. The second amplifier stage(Q2) is BJT common emitter amplifier with gain of +12 dB at the 100 Ohm load. This stage supplies voltage gain to compensate for the small capture area of the passive radiator. The ferrite transformer, L2 provides differential-to-single ended conversion and impedance matching to the 50 Ohm load. Fig. 3 and Fig. 4 show the measured gain and noise figure, and return loss of the fabricated active composite dipole antenna respectively. In comparison with commercial active vertical dipole antenna, HE309 produced by Rohde & Schwarz[9], even if the field strength sensitivity is degraded at the above frequency of 250 MHz (see Fig. 5), this antenna provides compact structure and resonable performance such as the noise figure of below 8 dB, the return loss of below −10 dB, the field strength sensitivity of below −34 dBuV/m with 1 Hz bandwidth, and the IP3 of 28 dBm over the wide frequency range.

The field strength sensitivity is calculated by assuming that signal to noise ratio(SNR) is 1 at the antenna output and external noise is zero. However, the filed strength sensitivity in the real world is degraded by external noise such as the cosmic noise toward galactic pole, the man made noise and the atmospheric noise. The noise functional relation to the frequency is mainly referred to ITU-R P.372-8[10]. Especially, man made noise which is varied from 30 dB to 10 dB at the interested frequency range dominantly degrades the antenna sensitivity. Fig. 6 shows the signal reception capability of the active composite dipole antenna for man made noise.

2-2 Five-Channel Direction Finder

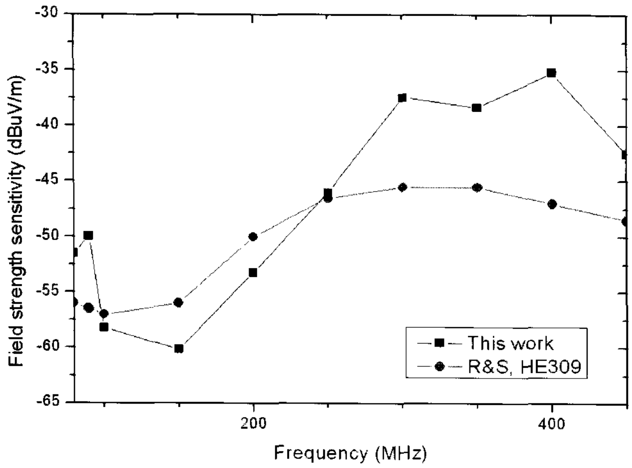


Fig. 5. Comparison of the field strength sensitivity.

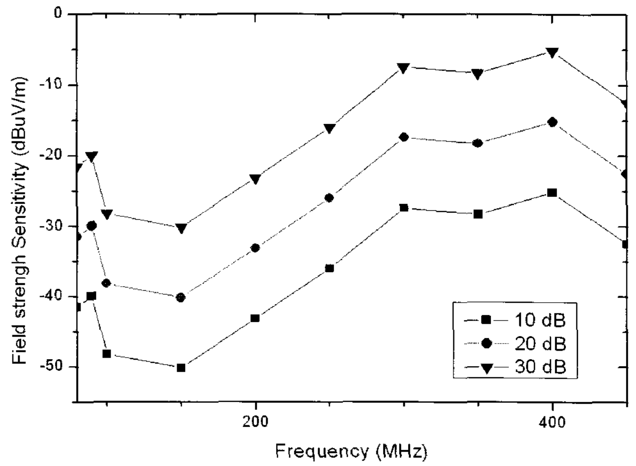
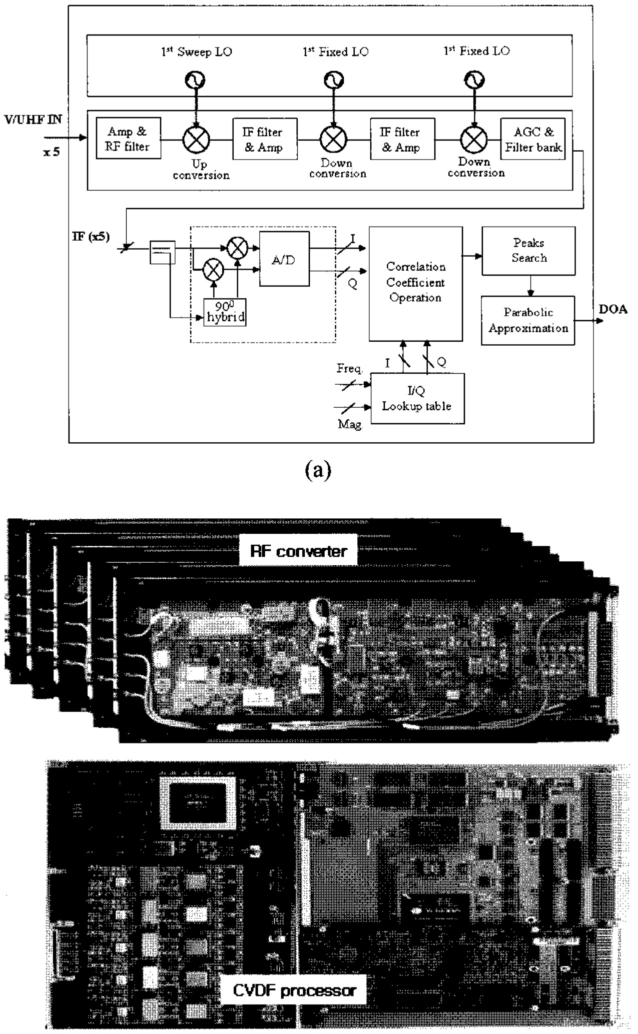


Fig. 6. Field strength sensitivity according to man made noise.

The multi-channel receiver requires less integration time and less signal to noise ratio for a given accuracy, and therefore provides faster response time than single-channel receiver. These properties are critical when a dense or rapidly changing emitter environment such as FHSS is targeted. Some important features are the selectivity and fast settling time of the receiver to avoid a mutual interaction of two adjacent signals and to intercept the short duration signals respectively. As shown in Fig. 7, the direction finder consists of the RF converter and the DF processor. The RF converter is designed as three-stage IF conversion structure to improve the selectivity and dynamic range. The IF placement is carefully selected to reduce the unwanted harmonics generated by nonlinear circuits. The received signals are amplified, filtered, and down-converted to an intermediate frequency of 10.7 MHz in the RF converter part. These IF outputs are sampled simultaneously by high speed A/D converters and then analyzed in the CVDF processors. The local oscillators are coherently split between the RF converters to keep the equal phase and amplitude in all RF converter sections. The DDS-based PLL is designed as the sweeping LO to improve the tuning speed and resolution. It consists of phase detector, loop filter, voltage control oscillator(VCO) and direct digital synthesizer(DDS) as shown in Fig. 8. The DDS output signal controlled by the frequency tuning word(FTW) is fed into the first mixer and then is mixed with the VCO output in the PLL feedback path. The employed DDS is tunable with a 32 bit word, equivalent to minimum frequency step of less than 1 Hz. The PLL module has a dual modulus prescaler that has pulse swallow function which makes it possible for the frequency synthesizer to generate higher output frequency and also finer frequency resolution. Since the VCO output is



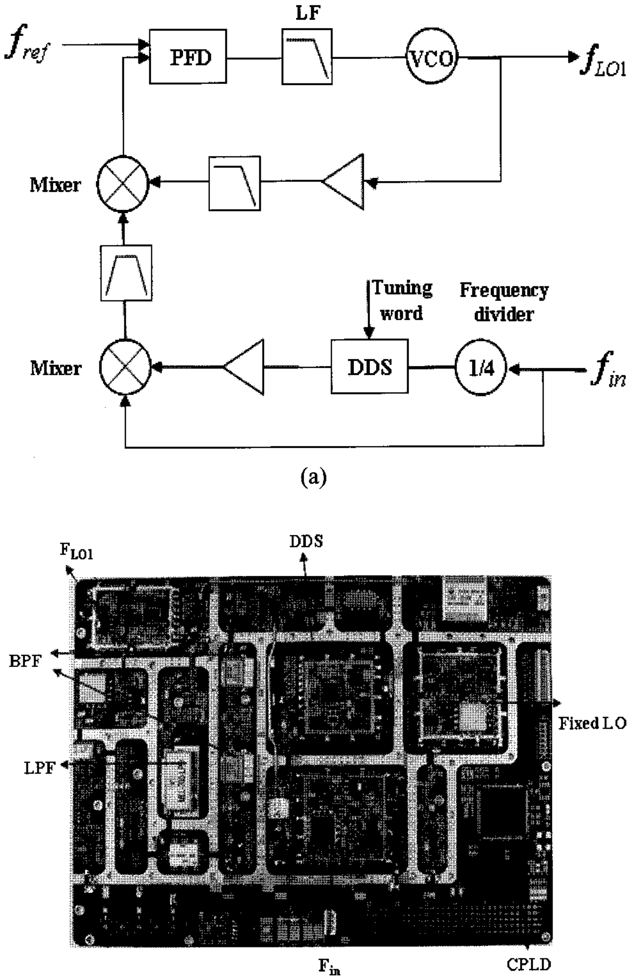
(a)

(b)

Fig. 7. (a) Configuration and (b) implementation of the direction finder.

phase locked to the DDS, the output frequency of the VCO changes rapidly according to the change of the DDS-offset frequency. This DDS-based PLL synthesizer allows the low phase noise of about -101.67 dBc/Hz at 10 kHz offset, fine frequency resolution of 1 Hz and fast settling time of around 26.6 *us* as shown in Fig. 9 and Fig. 10. The performance is summarized and compared with that of the synthesizers used in commercial V/UHF receiver in Table 1.

The CVDF processor is based on the ability to learn the response of the DF antenna array to received signals over all angles and frequencies. For each antenna element output, an IF is converted to a complex I/Q signal using Zero-IF concept which gives short processing time. A complex I/Q output describes the amplitude and phase of that element. The measured complex voltage vectors are correlated with those contained lookup table to search the maximum point of the complex correlation



(a)

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Fig. 8. (a) Configuration and (b) implementation of the DDS-based PLL synthesizer.

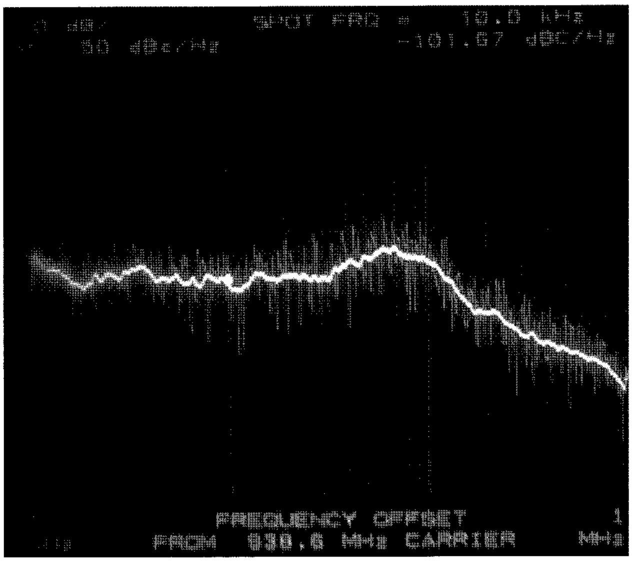


Fig. 9. Phase noise versus the frequency offset f_m from the carrier.

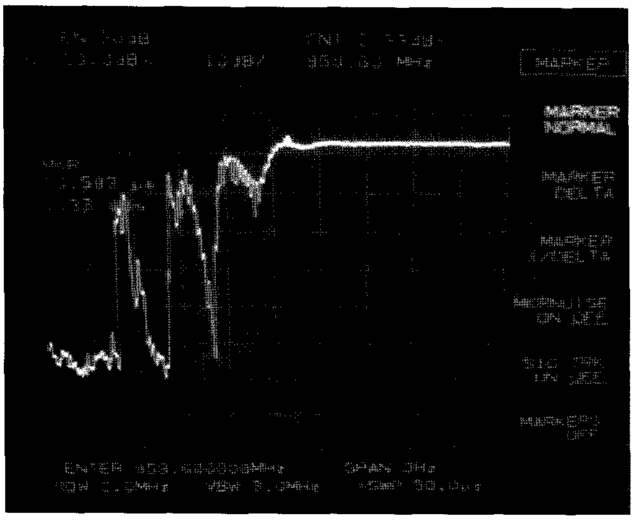


Fig. 10. Settling time from the carrier(f_r=1,138 MHz→f_n=858.6 MHz).

Table 1. Performance of the DDS-based PLL synthesizer.

	CUBIC[11] (CDR-4000S)	R&S[12] (ESMA-21)	This work
Application band	V/UHF	V/UHF	V/UHF
Phase noise	<−95 dBc/Hz @ 10 kHz	<−115 dBc/Hz @ 10 kHz	<−99.7 dBc/Hz @ 10 kHz
Frequency resolution	10 Hz	100 Hz	1 Hz
Settling time	700 *us*	150 *us*	<35 *us*

coefficient[3]. The sensitivity of the direction finder is influenced by IF bandwidth. The wider IF bandwidth allows more noise and thus reduce SNR. However, the IF bandwidth must be sufficiently wide to accommodate the bandwidth of the received signal. In typical V/UHF applications, the IF bandwidth of narrow FM voice communication is 15 kHz. To improve the sensitivity according to modulation methods such as CW, AM and FM, the selectable filter banks are inserted into the direction finder. Fig. 11 shows the field strength sensitivity of the direction finder for signal bandwidth at the SNR of 1. This sensitivity is added the effects of active dipole antenna.

2-3 Digital Search Receiver

The search receiver is designed as digital-IF FFT receiver using the field programmable gate arrays (FPGA) technology. Fig. 12 shows the operation diagram of the digital-IF FFT receiver architecture.

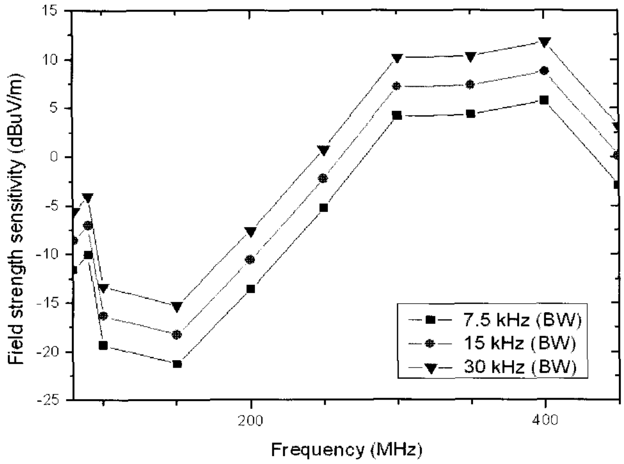


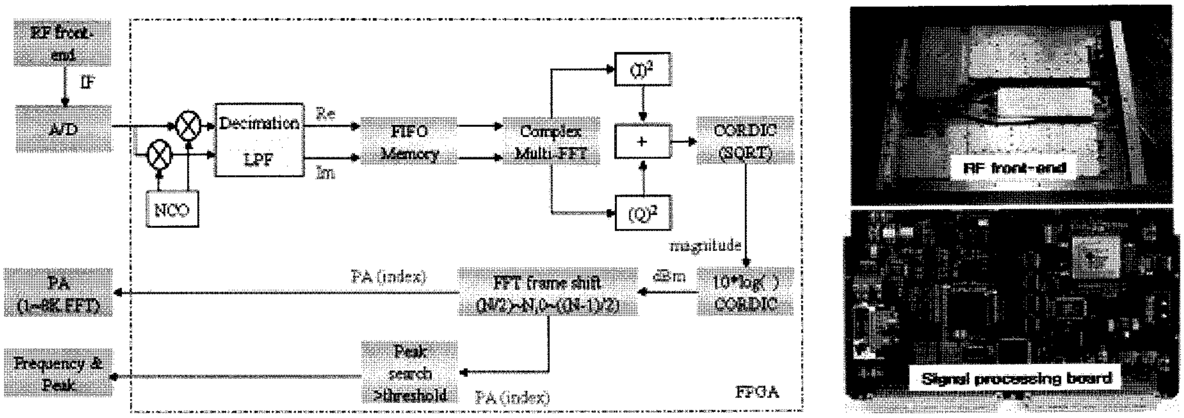
Fig. 11. Field strength sensitivity of the direction finder for signal bandwidth.

The IF signal is sampled by high speed A/D converter with sampling rate of 85.6 MHz and then fed to digital down converter(DDC) core to perform a dramatic reduction of the signal bandwidth from 85.6 MHz down to 10.625, 5.312 or 2.65 MHz. The sampling rate is also reduced by decimation values. The complex output of the DDC allows to fast compute a complex Fast Fourier Transform(FFT) power spectrum centered at 0 Hz. The complex FFT is implemented as the multi FFT structure applied by Radix-4 continuous algorithm[13]. This structure make it possible for user to control the FFT point from 1 K to 8 K. After time to frequency conversion in the complex FFT, CORDIC and peak search algorithm are carried out to calculate the magnitude and search the peaks of the signals respectively. The peak search data are provided with the direction finder through RS-422 cable. This digital-IF FFT receiver has characteristics of variable multi bandwidth and resolution, fast scanning speed of above 19 GHz/s, and high sensitivity of below 4 dBuV at 15 kHz bandwidth and 10 dB SNR.

Ⅲ. Performance Analysis and Measurement of the Five-channel CVDF System

The sensitivity of the CVDF system is defined as the minimum electric field strength of the wave front illuminating the DF antenna necessary for a specified bearing output threshold SNR. It is dependent on the gain and noise figure of the active antenna, the geometry of the active antenna array, external noise sources and the sensitivity of the direction finder. The system noise figure induced by active antenna, external noise and direction finder is given by[14]

$$F_{sys}=F_{ex}+F_{ant}+\frac{F_1-1}{G_{av,\,ant}}(1-|\Gamma|^2)+\frac{F_2-1}{G_1G_{av,\,ant}}\cdot+\cdots \qquad (1)$$



(a) (b)

Fig. 12. (a) Operation diagram and (b) implementation of the digital-IF FFT receiver.

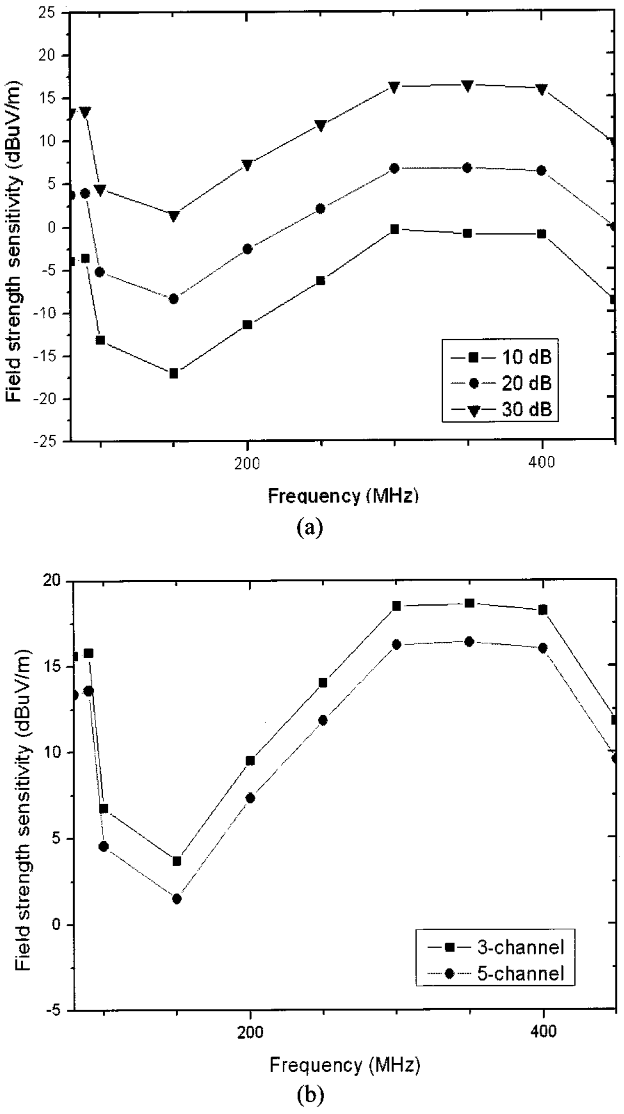
where F_{ex} is external noise figure, F_{ant} is antenna noise figure, $G_{av,\,ant}$ is available antenna gain, and Γ is the voltage reflection coefficient at the antenna terminals looking into the preamplifier and is given by

$$\Gamma = \frac{Z_p - Z_a}{Z_p + Z_a} \tag{2}$$

where Z_p is the impedance of the preamplifier and Z_a is the impedance of the antenna. Thus, $1-|\Gamma|^2$ is the fraction of power available at the antenna which is successfully transferred to the preamplifier. This fraction is nominally 1 but may be much less than 1 due to the impedance mismatch between antenna and amplifier. Given these findings, it is possible to determine the possible field strength sensitivity of the CVDF system that can be expected from the active antenna, external noise sources and direction finder. Fig. 13(a) shows the contributions from external and internal noise at the required SNR of 25.6 dB and the bandwidth of 15 kHz. We see that the field strength sensitivity is dominantly degraded by external noise sources induced by active dipole antenna. Fig. 13(b) shows the improvement of field strength sensitivity with regard to the number of channels in the worst case scenario that man made noise is 30 dB. It is resulted from the array processing factor.

The above field strength sensitivity discussion assumes that the array configuration is the wide aperture circular array with maximum ratio of $D/\lambda \leq 2.5$ such that it has sufficient DF accuracy and overcoming ambiguity and multipath problems where D is diameter of the antenna array and λ is wavelength of the received signal.

Usually, the DF accuracy is defined as the error in estimation of the AOA for signals with high SNR. It depends on several factors such as DF algorithms, antenna array types, modulation schemes, instrumental errors and environmental errors. The instrumental errors are induced by channel unequality in multi-channel receiver,



(a)

(b)

Fig. 13. (a) Field strength sensitivity of the five-channel CVDF system for man made noise and (b) comparison of field strength sensitivity of the five- and three-channel CVDF system.

thermal noise generated by receiver channel, and approximation in the signal processing algorithm. The environmental errors are site errors, interference errors, and propagation errors. To measure the potential DF accuracy of the five-channel CVDF system, the test setup is configured as shown in Fig. 1. A set of measurements is taken in laboratory test conditions using homemade test area and antenna array emulator to reduce the environmental errors[15]. Fig. 14 shows the measured AOA error of the five-channel CVDF system for D/λ. These results show the maximum AOA error of 1 deg. over the azimuth angle. Above measurements focus on CW measurements for evaluating the initial performance of the five-channel CVDF system. In the real scenario, the carrier signal is modulated signal. The modulation can introduce the AOA error due to the different envelop delay distortion in the direction finder. Fig. 15 shows the measured AOA error according to modulation schemes such as CW, AM and FM over the azimuth angle at the ratio of D/λ=2.14. The worst AOA error is achieved by FM signal. It can be caused by channel mismatch when processing wideband signals. The measurements are also taken to evaluate the AOA error of FM signals for D/λ as shown in Fig. 16. The AOA errors are becoming more increase at low frequency with fixed D as might be expected.

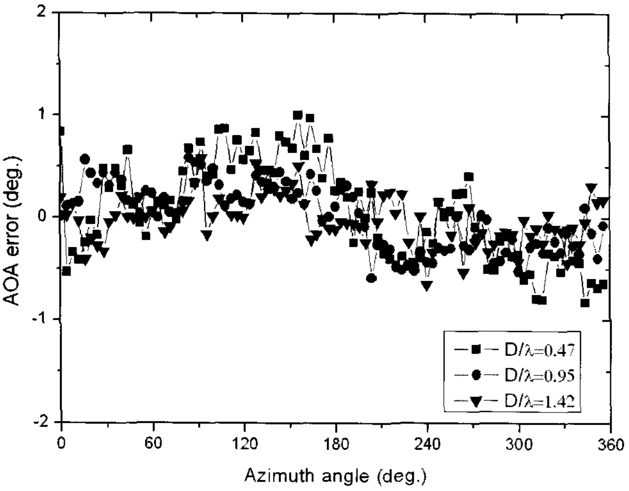


Fig. 14. AOA error of the five-channel CVDF system for D/λ.

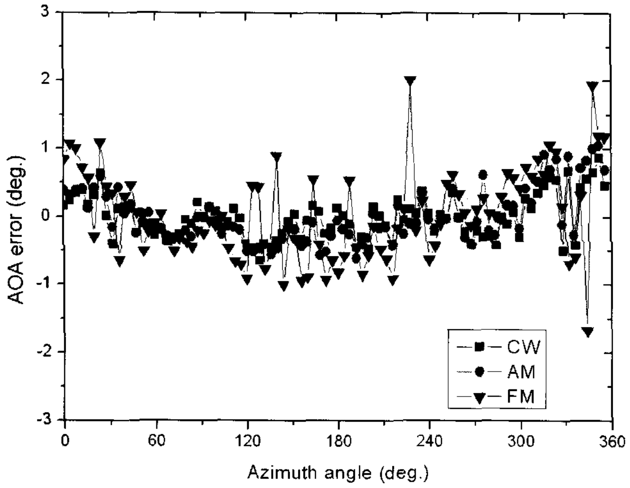


Fig. 15. AOA error of the five-channel CVDF system for modulation types(D/λ =2.14).

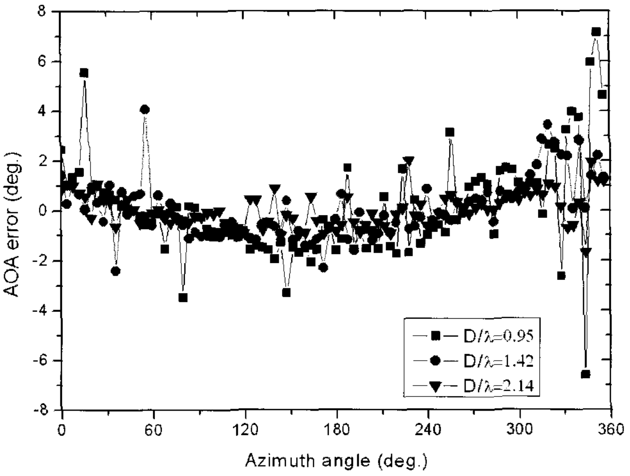


Fig. 16. AOA error of the FM signals for D/λ.

Ⅳ. Conclusion

In this work, we design and investigate the main elements of the five-channel CVDF system such as low noise broadband active composite dipole antenna, DDS-based fast tunable direction finder and digital search receiver with adjustable bandwidth and resolution. Their performances are compared with those of commercial products and analyzed according to external noise and signal bandwidth. To this end, the five-channel CVDF system is developed and evaluated via laboratory test conditions. The minimum field strength sensitivity for SNR of 25.6 dB is predicted by below 16.5 dBuV/m in the worst case scenario and the AOA error is obtained within 1 deg. versus azimuth angle in case that the modulated signal is CW. Although we need some additional improvement of the active composite dipole antenna such as field strength sensitivity at the above frequency of 250 MHz, the tuning resolution and scanning speed is superior than those of commercial receivers. These properties are useful for fast direction finding to intercept agile signals like FHSS at the dense signal environment.

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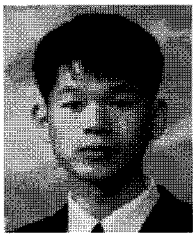

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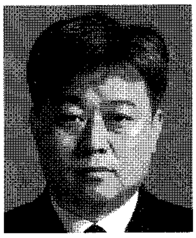

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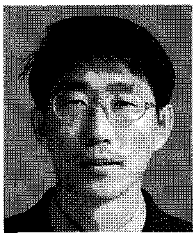

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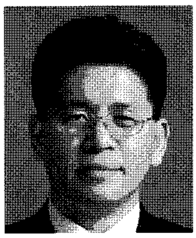

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