Performance Evaluation of MIMO Cooperative Radar by Considering High Altitude Aeronautical Platforms

Ashagrie Getnet Flattie

***Abstract*—** In this paper, an analysis of radar range and probability of detection by the use of multiple-input multiple-output (MIMO) radar with cooperative high altitude aeronautical platforms (HAAP) relay (which could operate at stratospheric altitudes) is presented. In this study, a method of cooperative diversity known as ampliy-and-forward (AF) is considered and a target fluctuation model (Swerling I, II, III &IV) which aspires to generate probability of detection (Pd) and probability of false alarm (Pfa) using HAAP relay proposed. Cooperative transmission with MIMO radar allowed extra degrees of freedom, diversity gain to enhance the radar detection, search, identification and tracking of objects in space or the atmosphere in a clutter/ electronic countermeasures environment. Matlab simulations show that the proposed scheme provides an excellent BER performance and lower required signal-to-noise ratio (SNR) compared with the conventional radar systems.

***Keywords*—**Cooperative, HAAP, MIMO, Radar, Swerling.

I. INTRODUCTION

RADAR theory has been a vibrant scientific field for the past decades. These radars, however, are known to exhibit detection and range estimation problems, hence jeopardizing the promised parameter identifiability, higher sensitivity to detect slowly moving targets [1, 2]. The performance of radar systems is limited by target scintillations. Targets are complex bodies composed of many scatterers. The range to, and the orientation of, the target determines the amount of energy reflected from these scatterers, and small changes in range or orientation can result in a large increase or decrease in the amount of energy reflected from the target [3] . To overcome these problems, several efficient approaches and radar performance has extensively been investigated in the literature [4-7]. For instance recent advances in multiple-input multiple-output (MIMO) technologies can be applied. MIMO is an emerging technology which consists in using multiple transmit and receive antennas in order to create spatial diversity between transmitter and receiver.

At the physical layer, MIMO is an emerging technology which consists in using multiple transmit and receive antennas in order to create spatial diversity between transmitter and receiver[8, 9]. Generally speaking, MIMO radar systems employ multiple antennas to transmit multiple waveforms and engage in joint processing of the received echoes from the target. Two main MIMO radar architectures have evolved: with collocated antennas and with distributed antennas. MIMO radar with colocated antennas makes use of waveform diversity while MIMO radar with distributed antenna takes advantage of the spatial diversity supported by the system configuration [10]. However, MIMO systems require multi-antennas devices, which may not be feasible in some devices due to cost and size limitations. The success of MIMO technology has led to the concept of cooperative communications where multiple nodes equipped with a single antenna cooperate together in order to form a virtual MIMO array and offer cooperative diversity [11, 12]. Thus the concept of cooperative diversity has been proposed to provide spatial diversity with single antenna devices.

In cooperative networks multiple copies of the source's signal are transmitted from source to destination with the help of cooperative relays and a direct signal is also transmitted from source to destination. Then any diversity technique for e.g. maximum ratio combining is used at the destination to reduce fading. Signal fading arising from multipath propagation is a particularly severe channel impairment that can be mitigated through the use of diversity [13-15]. Coupling the multiple-input multiple-output (MIMO) technology with a wireless relay network can offer significant improvement in spectral and power efficiencies [16] .The key challenges faced with distributed implementation of cooperative MIMO system are: (1) node coordination in sending and receiving groups, (2) distributed space-time coding and carrier frequency offsets in senders, and (3) data combining in the destination [17].

This paper attempt the cooperative MIMO for conventional radar and high altitude aeronautical platforms (HAAP) system to obtain better performance . A possible solution is to use high-altitude platforms (HAPs) or high-altitude very long endurance (HAVE) vehicles in the stratosphere has been recently proposed, which are either airships or planes that will operate in the stratosphere, at an altitude of 17–22 km above the ground. This unique position offers a significant link budget (line-of-sight Links) advantage compared with satellites and a much wider area of coverage than terrestrial using considerably less communications infrastructure than that required if delivered by a terrestrial network [18,19]. A HAP may be viewed as either a very low stationary satellite or a very tall radio mast. Wireless communications using HAPS have been proposed worldwide due to the many advantages of HAPS system over terrestrial and satellite systems since Stratospheric airplanes are more reliable [11,20].

Radar system sending electromagnetic (EM) waves, collect their returns, and process the recorded data to acquire information of a remote target or scene [21]. In this proposed

Ashagrie Getnet Flattie, Department of Engineering, Ethio-Telecom, Addis Ababa, Ethiopia.

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scheme, a transmitter side of radar (source) sends a signal to the target and the reflected signal received both the HAAP relays and a receiver side of radar (destination), see Fig.1. The HAAP relays retransmit the received signal about the same reflected signal to the destination and then, the destination combines the received signals from both the reflected signal (from the target) and the HAAP relays to enhance performance of the radar. In this way, multiple terminals in a network cooperate to exploit virtual multiple-input multiple-output (MIMO) benefits, and create a distributed form of spatial diversity the so-called cooperative diversity. Particularly, in a non-regenerative or amplify-and-forward (AF) relay system, the amplify-and-forward (AF) method which has advantages of simple implementation and low computational complexity ,i.e., the relays simply amplify the received signal from the source, and forward it to the destination without performing any sort of signal regeneration.

The remainder of this paper is structured as follows: Section II describes a general system model for cooperative MIMO radar with HAAP relay and expressions for the end-to end SNR are also derived. Section III reviews basic concept for HAAP and radar system such as, HAAP coverage, radar range equation, signal detection probability and false alarm probability. The simulation results comparing with the conventional radar schemes are given in Section IV. Finally, Section V concludes the paper.

II. System Model

In this section, the proposed model for cooperative MIMO radar and HAAP relay based system describe. Fig.1, consisting of a source, relay and destination nodes equipped with multiple antennas. There are N relays in the system. The source has Rs transmit antennas, the r-th relay has Mr antennas that are used for reception on the S-R link and transmission on the R-D link, and the destination has Md receive antennas. All transmissions are on orthogonal channels using binary phase shift keying (BPSK). Let $h_{d,s}$, $h^i_{r,s}$ and $h^i_{d,r}$ cannel coefficients of the source –destination, source-relay and relay-destination respectively. E_s is the average power of each symbol which is equal to $E\{x_n\} = P_s/N_t$, where P_s is the total transmit power per symbol.

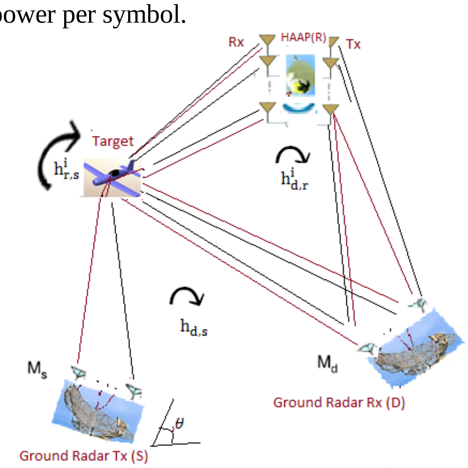

Fig.1. Scheme of conventional radar system with High Altitude Aeronautical Platforms.

Assuming all the time slots have unit duration, E_s can be considered as the transmission power. Further, the transmit power E_r available at the relay is assumed to be equally distributed among all the available antennas. $n_{d,s}$, $n^i_{r,s}$ and $n^i_{d,r}$ are additive circularly symmetric white Gaussian noise (AWGN) samples for S-D, S-R and R-D links respectively. The signals received at the destination (S-D) and the relays (D-R) are respectively [8-14].

$$y_{d,s} = \sqrt{E_s} h_{d,s} x + n_{d,s,} \tag{1}$$

$$y^i_{r,s} = \sqrt{E_s} h^i_{r,s} x + n^i_{r,s} \tag{2}$$

Where x is the transmitted information symbol, $n_{d,s,}$, $n^i_{r,s}$ and $n^i_{d,r}$ are additive noise modeled as having the same variance $\mathcal{N}_0$, i.e. $n_{d,s,}$, $n^i_{r,s}$, $n^i_{d,r} \sim \mathcal{CN}(0, \mathcal{N}_0)$.

In m subsequent time slots, the m relays use the AF protocol, i.e., normalize their received signals and retransmit to the destination one at a time. For the i_{th} relay, the normalization factor is $\sqrt{E\left\{\left|y^i_{r,s}\right|^2\right\}}$ (where $E\{.\}$ denotes the expectation operator) and thus the signal transmitted from the i_{th} relay applying the MRC to the received vector signal

$$x_r = \sum_{i=1}^{Mr} \sqrt{E_s}\, h^{i*}_{r,s} y^i_{r,s} \tag{3}$$

Based on "(3)", the signal received at the destination can be expressed as

$$y_{d,r} = \sqrt{\frac{1}{\sum_{i=1}^{Mr} \left|h^i_{r,s}\right|^2 E_s + N_0}}\ \sqrt{E_r} h_{d,r} x_r + n_{d,r} \tag{4}$$

Specifically, the equivalent received end-to-end SNR in this case is

$$\gamma_{eq} = \gamma_{d,s} + \sum_{r=1}^{N} \frac{\gamma^2_{r,s}\gamma_{d,r}}{1+\gamma_{r,s}+\gamma_{r,s}\gamma_{d,r}} \tag{5}$$

Where $\gamma_{d,s} = \frac{E_s}{N_o}\left|a_{d,s}\right|,^2$ $\gamma_{r,s} = \frac{E_s}{N_o}\sum_{i=1}^{Mr}\left|h^i_{r,s}\right|^2$ and $\gamma_{d,r} = \frac{E_s}{N_o}\left|h_{d,r}\right|^2$.

III. Basic Concept for HAAP and Radar

A. *HAAP Coverage*

The HAPs concept takes advantage of the advancements in microwave power transmission developments associated with the modern Solar Power systems and High Altitude Powered Platform concepts. HAPs are designed to fly at altitudes of around 22km (70,000 FT) because the average wind speed in the stratosphere is minimal at altitude of about 20 KM and at this altitude (which is well above commercial aircraft height), they can maintain a quasistationary position and support payloads[22,23].

In order to decide how much HAP is needed to provide the adequate coverage needed, we need to know the area covered by a single HAP. For a given platform altitude h, the diameter of the HAPS footprint can be computed using the formula:

$$d = 2R\left(\cos^{-1}\left(\frac{R}{R+h}\cos\theta\right) - \theta\right) \tag{6}$$

Where R is the Earth radius (6378 km), θ is the minimum elevation angle and the altitude.

B. Radar Range Equation

In this section the basic radar relations are reviewed in order to establish the terminology to be used throughout the study. The radar range equation (RRE) provides the most useful mathematical relationship available to the engineer in assessing both the need for and the resulting effectively of efforts to reduce radar target cross section [24]. One of the radar equations (for pulse radar equation) is [25].

When radar scans a whole space, with respect to the radar range equation, the maximum detection range satisfies

$$R^4_{Phase} = \frac{P_{av}A_r t_s \sigma}{(4\pi)^2 k T_s L_s (S/N)_{min}} \tag{7}$$

Where P_{av} is average transmitting power, A_r the effective receiving area, t_s scanning time, σ RCS, k the Boltzmann constant, T_s thermal temperature, L_s total loss, $(S/N)_{min}$ the minimum detectable SNR. Since only M elements of $M_t M_r$ virtual elements in MIMO radar are utilized to coherent a beam, the effective aperture areas is $A_r\frac{M}{M_t M_r}$. The detection range of MIMO radar satisfies [26].

$$R^4_{MIMO} = \frac{P_{av}A_r t_s \sigma}{(4\pi)^2 k T_s L_s (S/N)_{min}} \frac{M}{M_t M_r} \tag{8}$$

C. Detection Probability and False Alarm Probability

Signal detection probability and false alarm probability Pfa is usually given as the probability that an output pixel will have a value exceeding a specified threshold. In order to relate this per pixel measure to a system performance figure, the Pfa must be multiplied by the number of output pixels, and by the number of velocity filters applied to each data set [27].

The detection of radar targets against ground and sea clutter is a problem of great interest in the radar community [28].The detection problem is that of determination of the presence of a signal within the noise. For distributed targets, the probability of false alarm and the probability of detection can only be expressed in terms of multi-dimensional integrals, and are thus very complicated to obtain; in contrast, for point-like targets, such probabilities can be easily calculated by numerical integration techniques[29].The "detection probability" Pd is the conditional probability that, given that a signal is present, the signal-plus-noise falls within the range that will result in a "signal present" decision. A false alarm occurs whenever the noise voltage exceeds a defined threshold voltage, Vt, [30,31].

Mathematically, these quantities are given by

$$P_d = \int_{VT}^{\infty} dvp\left(\frac{v}{s}\right) \tag{9}$$

$$P_{fa} = \int_{VT}^{\infty} dvp\left(\frac{v}{n}\right) \tag{10}$$

Where VT is a chosen "threshold" voltage level, such that, if v(t) falls above that threshold, the decision will be "radar signal present" and if v(t) falls below the threshold, the decision will be "noise alone," and where p(v/s) and p(v/n) are the conditional PDFs of v given the condition "radar signal present" and "noise alone," respectively[32].For Gaussian noise

$$P_{fa} = \frac{1}{2}\left[1 - \mathrm{erf}(\widehat{V}_T)\right] \tag{11}$$

Where $\widehat{V}_T = V_T/\sqrt{2\sigma_n}$= threshold voltage normalized to $\sqrt{2}$ times the root mean square (r. m. s) noise level and $\sqrt{|R|} = |s|\sqrt{2\sigma_n} = \frac{1}{\sqrt{2}}(\mathrm{VoltageSNR})$, $u = \pm\sqrt{|R|}$ and $\mathrm{erf}(x) = 2/\sqrt{2\pi}\int_0^{\infty} dy^{e^{-y^2}}$= error function.

Considering that the radar signal is a sine waveform with amplitude A, then its power is $A^2/2$, $SNR = A^2/2\psi^2$(single-pulse SNR) and $V_T^2/2\psi^2 = \mathrm{in}(\frac{1}{P_{fa}})$ then

$$P_D = \int_{VT}^{\infty} \frac{r}{\psi^2} I_o\left(\frac{r^A}{\psi^2}\right)\exp\left(\frac{r^2+A^2}{2\psi^2}\right)dr$$

$$= \varrho\left[\sqrt{\frac{A^2}{\psi^2}}, \sqrt{2\ln\left[\frac{1}{P_{fa}}\right]}\right] \tag{12}$$

Marcum define as Pd which equal 10

$$\varrho[\alpha,\beta] = \int_{\beta}^{\infty} \mathcal{E} I_o(a\mathcal{E}) e^{-(\mathcal{E}2+a2)/2} d\mathcal{E} \tag{13}$$

Q is called Marcum'Q-function [32-34]. Many approximations for computing "(13)". can be found in the literatures. The very accurate approximation presented by North

$$P_d \approx 0.5\, xerfc(\sqrt{-InP_{fa}} - \sqrt{SNR + 0.5})$$

Where the complementary error function is [36]:

$$\mathrm{Erfc}(z) = 1 - \frac{2}{\sqrt{\pi}}\int_0^z e^{-v^2} dv \tag{14}$$

D. Detection of Fluctuating Targets

When a target is present, the amplitude of the signal at the receiver depends on the target radar cross section (RCS), which is the effective scattering area of a target as seen by the radar. In general, the target RCS fluctuates because targets consist of many scattering elements, and returns from each scattering element vary. Target RCS fluctuations are often modeled according to the four Swerling target cases, Swerling case I to IV. These fluctuating models assume that the target RCS fluctuation follows either a Rayleigh or one-dominant-plus Rayleigh distribution with scan-to-scan or pulse-to pulse statistical independence [33]. The constant RCS case analyzed by Marcum is widely known as Swerling 0 or equivalently Swerling V. Signal fluctuation lowers the probability of detection, or equivalently reduces the SNR [35].

a) Swerling Case I : is the case for most rotating, fixed frequency air surveillance radars, which is fluctuation is slow. The probability distribution function for signal plus noise is given by [33,35].

$$P(S) = \frac{1}{m_s} \exp\left(-\frac{S}{m_s}\right), S \geq 0 \qquad (15)$$

Where ms is the average cross section (average of RCS or signal-to-noise power ratio S) over all target fluctuations.

b) Swerling Case II : In this case, the fluctuations are more rapid than in Case I, and are assumed to be independent from pulse-to-pulse instead of from scan-to-scan. This is pulse-to-pulse fluctuation. The probability density function for the target cross section is the same as given in "(15)".

c) Swerling Case III : Swerling case III and IV are similar to cases I and II, but the object of interest has one major reflector and many minor ones. The echoes have a chi-squared probability distribution function with four degrees of freedom Swerling case III echoes have the same amplitude during a look and different amplitudes from look (scan) to look. The probability distribution function for signal plus noise is given by

$$P(S) = \frac{1}{m_s^2} \exp\left(-\frac{2S}{m_s}\right), S \geq 0 \qquad (16)$$

d) Swerling Case IV: In this case, the fluctuations are pulse-to-pulse as in Case II, but the probability density function is given by "(16)".

Swerling Cases I to IV are the models most commonly used, even though other models have been developed. They are summarized in the chi-square target models family by [37].

$$P_k(S) = \frac{1}{\Gamma(k)} \frac{k}{m_s} \left(\frac{kS}{m_s}\right)^{k-1} \exp\left(-\frac{kS}{m_s}\right), S \geq 0 \qquad (17)$$

Where $\Gamma(k) = (k-1)!, S = A^2/2\sigma^2$ is the target signal-to-noise power ratio (radar cross section), m_s is the average signal-to-noise ratio (mean cross section), $k = m_s^2/\,\mathrm{var}[S]$, σ^2 is the noise variance, and A is the signal amplitude. Table I shows the different Swerling target models for different values of k .

TABLE I
DIFFERENT CASES TO WHICH SWERLING MODELS APPLY SIMULATION ASSUMPTION

Model	K	Fluctuation		Scattere
		Scan-to -Scan	Pulse-to - Pulse	
Swerling Case I	1	√		Many Independent
Swerling Case II	1		√	
Swerling Case III	2	√		one dominant
Swerling Case IV	2		√	

TABLE II
SOME SIMULATION PARAMETER

Parameter	**Value**
Antenna gain	34 dB
Swerling Case	I, II,III,IV
Radar Height	20 m
HAPs Height	20 Km
Target Height	10 Km
Transmitter gain	31.6 dB
Effective temperature	290 K
Frequency	2.8 GHz
Antenna gain	34 dB
Target RCS	1m^2

IV. SIMULATION RESULTS ANALYSIS

In order to illustrate the above theoretical analysis, some Matlab simulation results are presented to demonstrate the performance of the proposed scheme. In this studies it is assume that a HAAP carrying a relay payload and a multi-beam phased array an altitude of 20 km in the stratosphere. In phase 1, the ground (conventional) radar transmit the signals to the target and the reflected signal reached to the destination and HAAP relay, simultaneously. The received signal at the HAAP relay is amplified and for warded (i.e., using AF protocol) to the destination in phase 2 at each power range value. Then combined the received signal from the source in phase 1 using MRC then combined the received signal vector from relay in phase 2 using MRC. Finally ground receiver demodulates the total combined signals from two phases using BPSK demodulator. Ground radar performance is compared with one and two MIMO cooperative high altitude aeronautical platforms (HAAPs). The result presents Bit error rate (BER) versus SNR, detection range versus power aperture product and finally probability of detection versus fluctuation loss in different Swerling case.

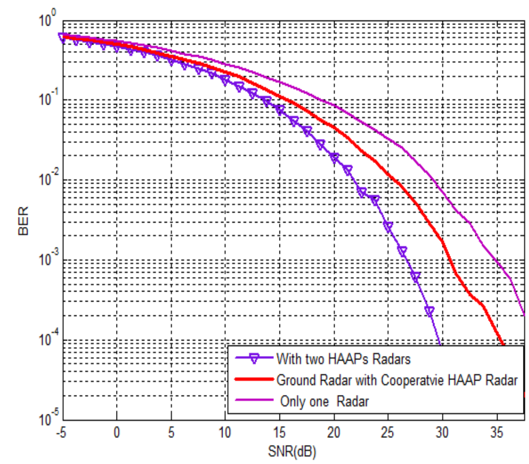

Fig.2 Performance Of Various Proposed Schemes Interms Of BER Versus SNR.

The performance of the three proposed scheme in terms of the BER for cooperative MIMO ground radar and HAAP relay system is shown in Fig. 2. The result shows that the BER performance of two HAAPs relay cooperative MIMO system is better than the BER performance of both conventional (only one radar) SISO system and a ground radar with a single HAAP cooperative relay system, e.g. with single cooperative HAAP relay and with two MIMO cooperative HAAP relay are able to provide gains of around 2. 5dB and 7 dB respectively over direct transmission (only one ground radar used) at BER 10^{-2}. In general tt can be seen that a significant performance improvement observed with based AF MIMO HAAPs scheme compared to using conventional radar.

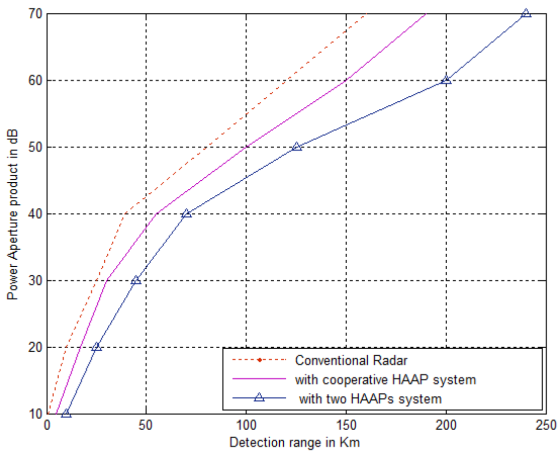

Fig.3. Detection range in Km versus Power aperture product for different proposed scheme when sigma = -20dBsm, BER 10-2.

As shown in Fig. 3 the performances of the cooperative HAAPS scheme with one and two relay are 20 Km and 45 Km away from those of the conventional radar when power aperture 50 dB. This is expected because the HAAPs MIMO cooperation scheme under consideration effectively realizes a distributed implementation of receive diversity. So the conventional radar system requires higher SNRs to provide the same performance for other schemes. This approach is able to increase search coverage, since the higher the required average received power, the lower the coverage, and vice versa"(7 and 8)". The same result obtained in Fig. 4 , except the performance is better when we apply sigma = 0 dBsm.

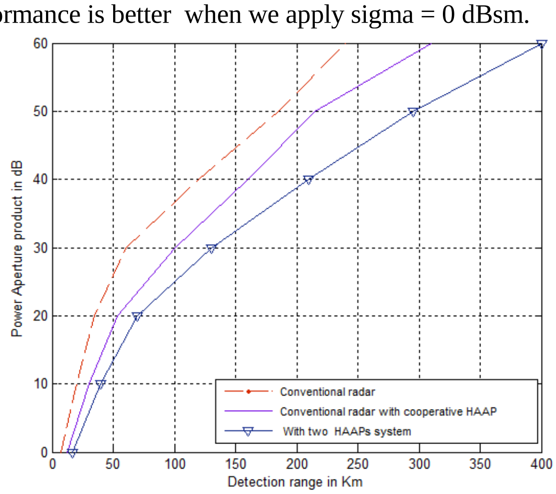

Fig.4. Detection range in Km versus Power aperture product for different proposed scheme when sigma = 0dBsm, BER 10-2.

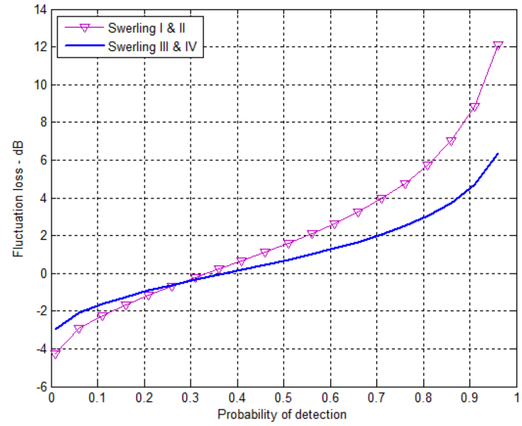

Fig.5. Probability of detection versus fluctuation loss for conventional radar system or one ground(SISO) radar (Pfa=1e-14,np=1) used.

For single pulse detection (n_p=1), the two detection probability SNR curves of Swerling I and Swerling II overlap which shows that they have the same detection performance.

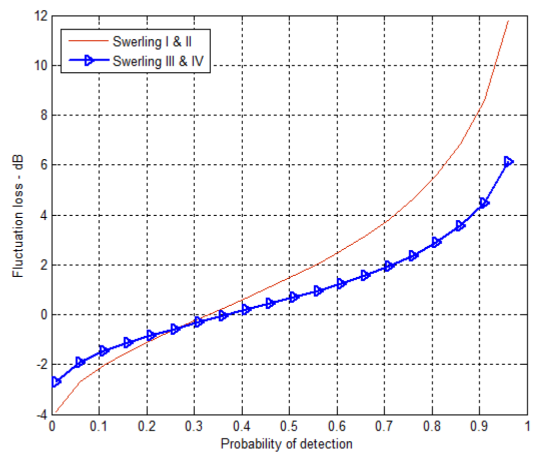

Fig. 6. Probability of detection versus fluctuation loss for ground radar system with one relay cooperative MIMO HAAP system (Pfa=1e-10,np=1).

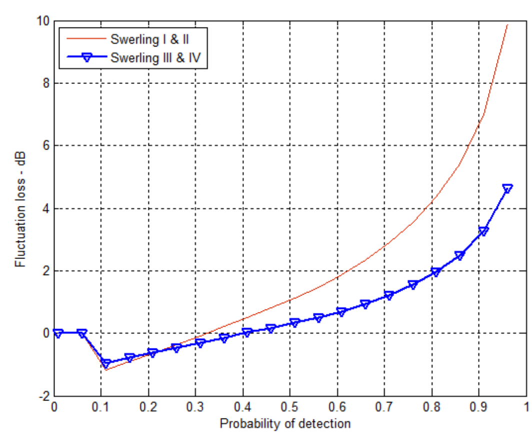

Fig.7. Probability of detection versus fluctuation loss for ground radar system with two relay cooperative MIMO HAAP system (Pfa=1e-2,np=1).

Similar result is observed in Figs. 6, and 7, however in this case the probability of detection is better than the conventional radar (see Fig. 5) for instance when fluctuation loss 2 dB and Swerling III & IV, the probability of detection improve 15 % when we applied two relay in cooperative MIMO HAAP scheme comparing conventional radar system. In short, the effect of the proposed methods is to minimize the require signal-to-noise ratio for high probability of detection and hence cooperative HAAP relay system can improve on conventional target detection, parameter identification, and target classification performance via diversity of, among other things.

V. Conclusions

This paper has presented a modeling scenario which includes multiple-input multiple-output (MIMO radar in a cooperative high altitude aeronautical platforms (HAAPs) relay with conventional radar system .Radar detection range and probability of detection simulation based on cooperative diversity in presence of a fluctuation target model is performed for the cases of single ground radar, with one cooperative HAAP relay and with two cooperative HAAP relays. The results show that the probability of detection for proposed scheme increase both Swerling case (I, II, III & IV) in same fluctuation loss. In addition to this the detection range also enhance with same value of power aperture product. The proposed methods suites for air surveillance radars are designed to detect, locate, track, search information with high data rate for low-flying aircraft and classify a wide range of targets. In addition to this the system provides the following advantage: ready for easy integration, full remote control, unattended operation and easily.

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