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Abstract

A Transmitter Independent Receiver Network (TIRN) is a network of radar receivers that operates in an area without cooperating with a particular radar transmitter, but rather using transmitters of opportunity (TOA) in order to detect and track airborne, ballistic or surface targets. In this paper a brief vulnerability analysis is given in both the detection/tracking and the communication subsystems of such a network. Electronic Defense (ED) solutions and interference avoidance techniques are given. A TIRN is mostly based in silent (low emission) operation and redundancy techniques. It is briefly described in the introduction. In the following paragraphs dealing with jamming techniques and is discussed, for both the detection and communication subsystems, comparing the results with the classic radar equivalent where applicable. It is finally concluded that such a network less vulnerable than conventional radars in most cases and in some cases even detect possible jammer effectively, at a fraction of the cost of classic radar net.

Keywords


1. Introduction: The Transmitter – Independent Receiver Network (TIRN)

A TIRN [1] is a development of an independent bistatic receiver or “hitch hiker” [2], in order to allow different modes of operation. Its diagram is shown in fig. 1. It consists of a number of radar receivers similar in construction to Electronic Support Measures (ESM) [3] receivers netted together and with processing devices over a communication network. The purpose of creation of such a network is to allow target detection and tracking using the signal of nearby non-cooperative (even non friendly at all) radars or other transmitters as signal sources. Its main modes of target detection are:

**Range Sum (RS):** This is the classic bistatic radar detection [4], [5], and it is useful in long-range target detection and as a last resort if the communication network between the receivers is cut. It demands that the position of the transmitting radar is known, (fig. 2) the signal is not plain Continuous Wave (CW). And the receiver antenna is of high directivity and good angular discrimination. A monopulse antenna [6] would give better results. For the special case, that receiver resides at $R_x(0,0,0)$ and transmitter at $T_x(R,0,0)$ then the location of a target in Cartesian coordinates is:
\[
x = \frac{(ct)^2 - R^2}{2(tc - R \cos \phi \sin \theta)} \cos \phi \sin \theta, \quad y = \frac{(ct)^2 - R^2}{2(tc - R \cos \phi \sin \theta)} \sin \phi \sin \theta, \quad z = \frac{(ct)^2 - R^2}{2(tc - R \cos \phi \sin \theta)} \cos \theta \tag{1}
\]

In the equation system above, \(\phi, \theta\) are the polar coordinates extracted by the receiver antenna azimuth and elevation.

**Time Difference of Arrival (TDOA):** It is used ranges a magnitude of order larger than the baselines (distances between the receivers) and it requires a signal with transients like the RS method. The receiver’s antenna pattern is irrelevant, confined only by the demand of relatively high gain. This mode is used for wide angle of detection. It can be used also for initial detection of the radar that is used as signal source. At least four receivers (fig.3) are required for three-dimensional detection. Hyperboloid sector equations are formed:

\[
\sqrt{(x-x_j)^2 + (y-y_j)^2 + (z-z_j)^2} - \sqrt{(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2} - c(t_i - t_j) = 0, \quad j = 2, 3, 4 \tag{2}
\]

In the above system, \(x, y, z\) are the target coordinates, \(x_i, y_i, z_i, i = 1, 2, 3, 4\) are the receiver coordinates and \(t_i - t_j = \Delta t_{ij}\) is the measured TDOA for two receivers. An Artificial Neural Network (ANN) can effectively solve this nonlinear system as described thoroughly in [7].

**Angle of Arrival (AOA):** This method is (fig.4) used strictly with high-gain monopulse antennas and the TIRN can detect targets and other transmitters by defining their azimuths and elevations from two receivers. This method is signal independent but in case if the signal is CW or similar (FM-CW, chirp) and at least four receivers are used it can give also three-dimensional Doppler velocity, useful for tracking and weapon guidance purposes.

This detection method can be described as follows: Let \(r_i(x_i, y_i, z_i)\) and \(r_j(x, y, z)\) be the locations of one of the receivers \((i \in \{1, 2, 3, 4\})\) and the target respectively. Then the equations connecting the Cartesian coordinates with the spherical coordinates measured on each receiver by its monopulse antenna are given below:

\[
x - x_i = R_i \cos \phi \sin \theta, \quad y - y_i = R_i \sin \phi \sin \theta, \quad z - z_i = R_i \cos \theta \tag{3}
\]

With the elimination of \(R_i\) (target receiver distance) it becomes:

\[
\begin{bmatrix}
\cos \theta & 0 & -\cos \phi \sin \theta \\
0 & \cos \theta & -\sin \phi \sin \theta \\
0 & \cos \theta & -\sin \phi \sin \theta
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
= \begin{bmatrix}
\cos \theta & 0 & -\cos \phi \sin \theta \\
0 & \cos \theta & -\sin \phi \sin \theta \\
0 & \cos \theta & -\sin \phi \sin \theta
\end{bmatrix}
\begin{bmatrix}
x_i \\
y_i \\
z_i
\end{bmatrix}
\tag{4}
\]

As it is clear, even two receivers would give an overdetermined equation system. All four receivers are needed if velocity vector determination is desirable in order to solve the Doppler velocity linear system:
Where: \[ v_{te} + v_i = - c \frac{f_{dmi}}{f_T} = \delta_i \] (5)

Above, \( f_T, f_{dmi} \) are the transmitted frequency and the received Doppler frequency, with a possible systematic error \( v_{te} \). This is because a common signal is used for frequency translation at all the receivers. It must be noted that TIRN can compete with these errors giving accurate velocity vectors as noted in [1] and thoroughly in [8] where ANN are also using for solving these linear systems.

Although the receivers are totally passive a secure communication network must be established between the receivers. In a jamming environment the receivers and the network are possibly vulnerable. In the paragraphs to follow the redundancy needed in the design of a TIRN is explained, and simple techniques are proposed to overcome possible EA cases. Simplicity is kept, because the TIRN is intended for military use with the ease of personnel training and rapid network deployment in designers’ mind.

2. Radar Jamming.

Radar jamming in general form is either barrage/spot jamming or some form of deception jamming.

**Barrage and spot jamming** is the oldest method of EA and it is simply the transmission of a high power continuous noise-like signal in order to decrease the SNR at the victim radar’s receiver. It can be used by the target aircraft itself as self protection jamming (SPJ) or by escort aircraft usually dedicated to EA/ED missions (escort jamming usually stand off jamming – SOJ or stand in jamming – SIJ).

In order to be power effective the bandwidth of the jamming signal must be marginally larger than the radar receiver’s filter. This case is explained thoroughly in [9], and it is called spot jamming throughout military literature. In case of the passive multistatic radar though it can not be a real threat since with AOA mode of operation the jammer makes itself clearly visible. In fact the detection can be done in greater ranges that leaving the radar illumination alone.

TDOA on the other hand may be seriously affected due to the continuous signal the jammer transmits although Doppler velocity discrimination is still possible if the jamming signal is processed.

Anyway for each receiver the signal is given by the bistatic radar equation:

\[
S = P_T \frac{G_{TX} \cdot G_{RX} \cdot \lambda^2 \cdot \sigma(\alpha)}{(4 \cdot \pi)^3 \cdot R_{TX}^2 \cdot R_{RX}^2}
\] (6)

The parameters are \( P_T \), the power of the transmitter (Watts), \( \lambda \) the wavelength in meters, \( \sigma \) the bistatic RCS at bistatic angle \( \alpha \), \( G_{TX} \), and \( G_{RX} \) the transmitter and receiver antenna gains (ratios to isotropic) and \( R_{TX} \), \( R_{RX} \) the distances of the target from the transmitter and receiver respectively.
The power at the receiver of the SPJ signal (with correct IF filter match) is given by the equation below:

\[ J = P_j \frac{G_j(-\phi,-\theta) \cdot G_{RX} \cdot \lambda^2}{(4 \cdot \pi)^2 R_{RX}^2} \]  

(6)

Note that the gain of the jammer might be either directional or omnidirectional. In the first case the possibility of unveiling a TIRN receiver to direct its antenna and investigate its illuminator is low but even if it happens there are at least three more receivers in different angles suffering minimal consequences. For the jammed receiver the direction of the jammer is more than clear. Scanning this direction though may well unveil the jammer and other possible targets in close or loose formation.

If an omnidirectional antenna is used by the jammer Signal to Jamming Ratio is then depending only on the distance from the transmitter:

\[ S = \frac{P_{TX} \cdot G_{TX} \cdot \sigma(\alpha)}{P_j \cdot G_j(-\phi,-\theta) \cdot 4 \cdot \pi \cdot R_{TX}^2} \]  

(7)

That simply means that the jammer gives another signal for the AOA detector to work with, a point noise source into the bandwidth the receivers were tuned. The jamming signal is irrelevant to the TIRN transmitter distance. So the TIRN may use the Transmitter signal when the jammer is near to the transmitter or the jammer signal if the jammer is near the receivers’ area.

In fact even Doppler may be extracted if using subsystems as described in figure 7. Doppler shift is visible in Fig.8. Note that the source signals are just filtered white noise.

In the case of escort jamming the case is somewhat different. Then the targets may be discovered the usual way and the jammer aircraft by the technique described before.

**Deception Jamming** is the repetition of the radar signal in a way that simulates the original in order to deceit the radar range detector or Doppler detector. The EA signal then is modified by delay or frequency shift respectively. [9], this must be done by staggering the PRF or modulate with an acoustic frequency. In the TIRN case that might be lethal to the jammer itself while leaving TIRN almost fully operational.

Eq.6 still stands in this case with all its benefits. AOA in this case is fully operational (The jammer is seen as a large target). TDOA might be preferred especially if the TIRN transmitter and the deception jammer uses some low PRF waveform. Separation of escort jamming is an easy problem also as shown before.

3. **Communication Jamming.**

Hostile action could be taken against the communication network that interconnects the receivers and command posts. So the network topology must be as robust as possible. Since a TIRN must be essentially a robust and system the most secure communication links must be established between the receivers and the command posts in a star or mesh topology, in order to survive even the loss of one transceiver.
Anyway spread spectrum techniques or even chaotic communication techniques maybe used, mainly to avoid uncovering the TIRN elements if they are mobile. Adaptive arrays and the use of as low as possible communication power with a form of back-off mechanism for the network must also used to minimize the possibility of signal intelligence. Dedicated transmission line communications may be considered in larger static installations.

4. Conclusions

As regards the RS method, it is totally immune to communication jamming but possibly vulnerable to barrage and deception jamming if the receiver location is estimated properly. This is not surprising since an independent receiver is similar to a single radar receiver. It can be considered though as less vulnerable than a radar since it is more difficult to be detected. Even so there are four at least receivers difficult to be jammed at the same time.

If the TIRN is using hostile radar as signal source, jamming the passive receiver but leaving the active radar intact is an interesting problem for the hostile jammer.

On the other hand if the network is robust enough to withstand communication jamming, the other two methods (TDOA and AOA) can unveil the radar signal jammers. Adaptive array techniques alongside with Spread Spectrum and diversity techniques may solve most wireless communication jamming problems.

The advantages and disadvantages of TIRN are shown below.

<table>
<thead>
<tr>
<th>System/Case</th>
<th>Monostatic</th>
<th>Bistatic</th>
<th>TIRN (AOA)</th>
<th>TIRN (TDOA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrage/spot SPJ</td>
<td>Vulnerable</td>
<td>Vulnerable</td>
<td>Immune</td>
<td>Vulnerable</td>
</tr>
<tr>
<td>Barrage/spot escort</td>
<td>Vulnerable</td>
<td>Vulnerable if uncovered</td>
<td>Immune</td>
<td>Vulnerable</td>
</tr>
<tr>
<td>Deception</td>
<td>Vulnerable</td>
<td>Vulnerable if uncovered</td>
<td>Immune</td>
<td>Immune</td>
</tr>
<tr>
<td>Communication</td>
<td>Immune</td>
<td>Immune</td>
<td>Vulnerable if uncovered</td>
<td>Vulnerable if uncovered</td>
</tr>
<tr>
<td>Doppler</td>
<td>Radial only</td>
<td>MTI only</td>
<td>3D-Full</td>
<td>3D-MTI</td>
</tr>
</tbody>
</table>

It is now clear that a multimode TIRN has a lot of probability to first detect and then accurately track an ECM equipped aircraft and confront them.

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![Acknowledgments](image)

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References:


Appendix: Figures and Diagrams.

Fig. 1: The passive multistatic radar (TIRN).

Fig. 2: Range Sum detection.

Fig. 3: TDOA detection.

Fig. 4: AOA detection.

Fig. 5: Types of Jamming in monostatic radars

Fig. 6: Types of escort jamming (monostatic radar case)
Figure 7 Relative Doppler 2 receiver subsystem.

Fig. 8 Relative Doppler (1/4 of IF bandwidth)