The Matrix: A Roadside Wireless Security System

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Abstract:

Over the past decade, worldwide increases in terrorist activities by both state and non-state actors has created a need for a real-time monitoring system that can identify and classify potential threats from a safe stand-off distance. Specifically, since the beginning of both the Iraq and Afghan wars, a major concern for coalition forces has been maintaining security for their bases, convoys, troops and equipment. The ability to procure safe access to bases and outposts as well as oft traveled routes, such as roads for supply convoys remains a primary security concern. In modern asymmetric warfare, hostile threats are often distributed over large distances, in harsh environmental conditions, and thus cannot be monitored adequately using current technology. A search and seizure is one example among many where wireless security can aid in the protection of military forces. As a result, automated roadside detection and classification is vital for personnel safety and government security.

In the past few years, wireless sensor networks have been demonstrated to be capable of accurately and reliably detecting objects using Radio Tomographic Imaging techniques developed by Wilson and Patwari [1]. This paper presents the design and development of an enhancement of these wireless sensor networks by incorporating object recognition and classification. The enhanced network, known as “The Matrix” will be able to autonomously monitor remote roads, identify potential security threats, and alert a command and control center if security measures need to be activated.

I. Introduction

Troops in Iraq and Afghanistan are faced with patrolling more roads in and out of regulated zones than they can support. There is a necessity for a real-time road monitoring system that can monitor roads and stop enemies from getting through the cracks in our current road patrol system. The system should be integrated with a command center resulting in a network of roads being monitored simultaneously for enemies.

The purpose of our project is to design a wireless sensor network that will be used to identify a target and deploy a security measure if necessary. The network will be positioned to implement the desired security device if an object enters the field and is deemed an enemy by passing through a specified height level without a unique RF signal. This project is extremely relevant to modern wars, as enemies are spread over such a great distance that roads cannot be monitored adequately or safely without the use of technology. Typical security measures are limited by the quantity of manpower and directionally limited by sight. An automated wireless system offers more robust and persistent surveillance than manual labor. The Wireless “Matrix” can be set up along a road in order to detect hostile vehicles via Radio Tomographic Imaging (RTI).

The aim of this project is to expand upon the 2010 design and prepare for practical friendly blue cell applications [2]. Specifically, this project incorporates wireless object classification by using a three-dimensional system vice the one-dimensional system used in the previous design. The output from the wireless matrix will be displayed to allow for the final manual decision, optimizing security and preventing indiscriminate attacks.

The project objectives included creating the sensors needed to meet the requirements of the
wireless matrix and the language that will be used for the sensors to talk to one another. The wireless network uses multiple poles, each with three sensors placed upon them at various heights to create a three-dimensional view of the road being monitored. The received signals of each pole monitor for changes and the data will be used to detect and classify the target.

II. System Design

A. System Design Objectives

Taking into account the mission objectives, military needs and the user needs, the following requirements were determined for the device:

1. **Reliability** - To convey accurate data, the wireless network must have a high error tolerance during transmission, encoding, reception and decoding of the aggregated node signals.

2. **Continuous Operation** - The nodes need to constantly operate based upon operation requirements for detection. In a military environment, a preventative system must always be scanning and searching.

3. **Calibration** - The system must be easily calibrated for use in what the military specific weather and temperature conditions.

4. **Mock 3-Dimensional** - The system should be able to detect the general height and size of an object. This is important in distinguishing between multiple vehicles/obstructions.

5. **Robust to Multi-path** - To get accurate information the sensors must be able to cancel out noise and reflections of the transmitted signal on a consistent basis.

**Overall Network Design Architecture**

The network was comprised of a 24 pole design with one node per pole. Each node has an antenna that both transmits and receives data allowing each node to store data from every other node in the network.

![Wireless Node Network](image)

**Figure 3: Schematic of the Surveillance Network [2]**

To ensure the robust operation of the network and accurate detection method, each receiver node is in direct communication with every one of the other 23 transmitting and receiving nodes as well as the command and control node. Each node in the network, depicted in Figure 3, independently transmits their received signal strength, RSS, and receives each of the other nodes RSS values upon the signal of the command and control node. The independent operation of each node ensures continuing operation of the network should any of the nodes go offline. The aggregated data from each node’s RSS values wirelessly detect any obstruction within the network.

For optimal network coverage a three-dimensional sawtooth waveform was chosen for wireless detection. The sawtooth configuration was demonstrated to have the highest object resolution [2] and provided the best target differentiation. The calculated resolution of the wireless network utilizing the sawtooth design is displayed in Figure 4. In the figure, we observe the three viewpoints show the networks wireless coverage from above, alongside the road and in the middle of the road entering the surveillance area.

Although the proposed network depicts an area of exposure of twenty-four nodes in length, multiple nodes may be added to cover a larger section of road or vice versa. The number of nodes is only limited by amount of data each node can send as well as transmission time. Using the current XBee pro module, at a maximum each node can send up to one hundred stored RSSI values limiting the number...
of total poles in the network to 101 nodes, without 
upgrading the xBee antenna and software [3].

Figure 4: Wireless Sensor Coverage of Saw Tooth 
Design from Different Viewpoints within the Wireless 
Network [4]

Other possible upgrades for the network 
include changing channels during each scan to avoid 
enemy interference such as jamming. Changing 
frequencies could also be done as a response to 
losing nodes on the network in an effort to escape a 
wireless enemy attack.

Node Design

The transmitter/receiver nodes and the 
command and control node were constructed 
identically in their hardware design and vary only 
through programmed software modifications. Figure 5 shows an in-depth schematic of the node 
designed and shown in Figure 6.

Each node is comprised of a power source, 
voltage regulator, microprocessor, and xBee 
transmitter/receiver. A 6 volt SLAB (sealed lead 
ad battery) powers the voltage regulator with an 
output of 3.3 volts used to power the other 
components on the board. A hex buffer was placed 
between the microprocessor and the xBee to avoid 
capacitive loading the pins on the Pic processor. 

Various LEDs and pin headers where also 
built into the board for troubleshooting purposes. 
The MAX322 chip was used produce the 12 volts 
needed for header J2 in order for computer serial 
interface with the board. This interface was very 
useful when gathering data from the command and 
control node allowing integration with other RS-232 
devices.

The microprocessor in Figures 5 and 6 is a 
DSPIC33FJGP302. The program code utilized the 
XBees Advanced Peripheral Interface (API) mode in 
the transmitter receiver and the command and 
control nodes. Enabling API mode ensures a 
specified packet format for ease of transmission with 
the RSSI value specified as part of the API data 
packet.

The RSS output from the PIC 
microprocessor is utilized to detect and classify the 
presence of an object. If the path between any of the 
XBee radio module is obstructed, the RSS will read
a lower value for the transmission between those two nodes. Therefore, if an object such as a vehicle obstructs the XBee radios, then a low RSS value will be output from the corresponding PIC. The array of RSSI value from each PIC is used to construct a two dimensional picture of the object, both horizontally and vertically as it moves through the system. Furthermore, the change in RSS values will indicate the speed at which the object is moving through the Matrix.

Upon processing the RSS values the accurate detection of the object will be confirmed and the Matrix will perform target identification and classification. This classification system will allow facilities to safely observe and take proper security actions with decreased risk to personnel.

Data Collection and Detection Algorithm

Detecting and distinguishing the size of an object are the main focuses of our wireless system. For detecting any obstruction, the observed drop in signal strength indicates that an object is obstructing the signal path. Essentially, each node transmits its own signal with its corresponding signal strength in a time divided scheme illustrated by Figure 7a and b. First, the command and control node sends a start message to trigger each of the transmit/receive nodes to begin data transmission. Upon receiving the start message from the command and control node the first node transmits in the first time slot while every other node listens for its RSS value. The system’s internal operation for the first and second time slot is depicted in Figure 7. Figure 7 displays each node communicating with one another while the command and control node aggregates the network’s data.

Specifically, Figure 7a shows the first node transmission, which is then followed by the second node transmitting in the second time slot as shown in Figure 7b. An entire network scan consists of each individual node transmitting its data once. Each node continues to transmit in turn while each other node receives and stores the received signal strength from the transmitting node.

While the transmit/receive nodes transmit their own received signal strength they also send a data array containing every other transmitted node’s stored RSSI values. The command and control node stores each array of transmitted RSSI values from every node, compiling the matrix of RSSI values for object detection. The collection and processing of the array of signal strengths is then used to construct the “picture” of the object for classification.

To implement the time division multiple access scheme, TDMA, for data transmission in the network, each node was programmed to transmit at a specified time within a loop, triggered by the C2C node. Below, Figure 8 shows the simplified flow diagram for the C2C node and the TX/RX node.
The timing for each scan, determined by the software loop shown in Figure 8, plays a significant role for determining the speed for detection. There is a limit to how fast an object may travel through the network to be accurately detected. Ultimately, this limit is determined by the ability of the XBee antenna to communicate from one antenna to another. Therefore, the speed for detection is dependent upon two parameters, the amount of data sent during each network scan and the data rate of XBee. Using the XBee Pro antenna the data rate is 115.2 kbps [3]. Therefore, the amount of data sent during each network scan must be within a time window to satisfy Equation 1 below. The Time required for each scan must then be used to calculate the speed for detection as shown in Equation 2.

\[
\frac{kbits}{NetworkScan} + 115.2 \text{ kbps} \times 1.2 = TimeForScan \quad (1)
\]

\[
\frac{ResolutionDist.}{TimeForScan} = SpeedForDetection \quad (2)
\]

Above, in Equation 1, a factor of 1.2 is used to give a buffer time of twenty percent for data processing during each scan. The resolution distance is then used with the time to scan to calculate the speed for detection. The resolution distance is a parameter determined by the network setup while the kbits per Network Scan can be calculated as shown in Figure 9 below.

\[
\text{Total Bits} = \frac{\text{# of TX/RX Nodes \times RX Data Pieces} \times 8 \text{ bits/character} \times \frac{\text{Number of Network Scans}}{\text{Packet by Each TX/RX Node}}} {10^3} = \frac{kbits}{Network Scan}
\]

From the above calculations, the wireless security data rate and amount of time it will take to scan the network once can be determined. It can be seen that the speed for detection is directly proportional to the number of nodes in the network. The Matrix was initially designed for ten miles per hour with a resolution distance of 0.75 meters remaining within the XBee data rate limitations.

**Testing and Results**

The wireless three-dimensional detection and classification Matrix is a continued project from the two-dimensional wireless detection network Smith and Uchida constructed in 2010. Expected RSSI values can be analyzed using Smith and Uchida’s data collected from their eight node test conducted in April 2010.

Smith and Uchida had constructed their network with four nodes on each side with only one side transmitting and the other side receiving only as displayed in Figure 10.

Currently, two phases of initial testing for the 2011 Matrix have been completed. The initial phases of testing consisted of one transmit and one receive node to collect data for a decision algorithm. The next step was a six node test run for data
collection on April 22, 2011 (results displayed in Figure 11). During the 6 node testing, measurements were taken with free space, a large van, a small car and uniformed personnel as a basis for network calibration to distinguish between such objects. Figure 11, below, shows the three objects used for data collection.

For testing, the objects depicted in Figure 11a, b, and c, were placed in multiple positions throughout the network while the wireless matrix was in operation. In the following figure, Figure 12, the test design is shown with all three test positions. Additionally, RSSI measurements were also taken for the uniformed personnel at a position between position one and position two and a position between two and three.

The 6 node test showed much promise and proved to be a success conceptually. An example of the attenuated values recorded for the Van from Figure 11a is shown in Figure 13. The values were averaged over five system runs for more accurate results.

Note that the highest attenuation changes are in the expected places, such as the signal sent from Node 2 to Node 5. This proves that the system worked in terms of detecting an obstruction. A diagram of the Van with its corresponding attenuation values is shown below in Figure 14.

The next step was proving that the system could actually detect and classify the object as it moved through the network. This too was successful with the results shown graphically in Figures 15 and 16 for both the Van and the Electric Car.
As seen in the figure, Frames 1, 2, and 3 showed the progression of the vehicle through the network. Based off of the attenuation densities, one can clearly see that the Van attenuated the signals much more in the network, especially at the beginning. The Electric Car was also barely detected until it reached the 0.5 meter poles, showing that its relative height was accounted for.

### III. Conclusion

Wireless signals with obstructions between them will experience signal losses due to multi-path caused by reflection, refraction, and shadowing. Detecting and classifying vehicles moving through a wireless surveillance network is of interest to the military and will be an asset in the Wars in Iraq, Afghanistan, and in preventing future acts of terrorism.

Detecting multiple objects, identification of friend or foe, and additional security features to the network itself are all areas that need to be addressed. There will always be areas for improvement, but the key is staying one step ahead of the enemy.

Looking to the future, the successful implementation of this project will help the military prevent numerous terrorist attacks while reducing the number of troops needed to monitor roads. Less troops means less lives in danger. In a commercial aspect, this design will help increase the general security of plants and industrial complexes from similar acts of terrorism.

### IV. References


