Real-time Monitoring of Explosives Using Wireless Sensor Networks

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ABSTRACT

An increase in bomb attacks in present era has boosted the need to have a continuous monitoring of explosives in public places. This paper proposes an effective warning mechanism for security threats in public places such as railway stations so that security corps can take immediate action against bomb threats. Using a multi phase wireless sensor network, the system will provide a technique to reduce, control, and warn about the forthcoming terrorist activity by accurate and fast detection of explosives. Multiple wireless sensor nodes integrated with different types of sensors is used to identify the chemical composition of explosives. Based on different orthogonal techniques, the system collect data from the sensing nodes dynamically aggregate the data and forward to the sink node for further analysis. A mobile node has been introduced to confirm the suspected objects, thus contributing an enhanced target tracking mechanism that reduces number of false alarms.

General Terms

Design, Algorithms

Keywords

Wireless sensor network, real-time monitoring, explosive detection.

1. INTRODUCTION

In recent years, terrorism is a main threat to the security of the world. According to global terrorism data base [1], the terrorist attacks are increasing in present days. In terms of total terrorist attacks between 1970 and 2007, India is ranked in the fifth position in the list of top ranking countries. It is also found that nearly 50% of weapons used were explosives. The explosives used were readily available, especially dynamite, grenades, and improvised devices placed inside vehicles. Remote monitoring for detection of explosives helps to improve the security of infrastructure and general public in urban areas. A wireless sensor network could be used for continuously monitoring and identifying explosive materials. Current systems in operation were not developed to function remotely in open environments in a wide area. The difficulty with the existing techniques is that the suspected items have to bring nearer to the detecting instrument. This involves more human involvement in the detection and cannot be continuously monitored. Here comes the significance of remotely detecting the explosives were the process of detection is taking place at a reasonable distance from the suspected material without affecting the other people occupied in suspected area.

This paper describes a continuous monitoring system for the detection of explosive materials in public places with the help of wireless sensor network technology [2-3]. The area under study is monitored in real time, collect data, aggregate it and send to the sink node. The system will work by analyzing the patterns that appear suspicious and raising alerts when it confirms the presence. The main constituent of explosives is chemicals. By analyzing the chemical signatures, it is almost possible to predict whether a material is explosive or not. The system exploits more than one type of independent technique to capture the presence of explosive material that makes the detection process very effective. In an open environment, a single type of sensor may not be adequate in confirming the explosive material presence. Also the concentration of these materials will be very less in the atmosphere because of its well packing. These may cause wrong alarms and destroy the usefulness of the system. To meet this limitation, the system uses more than one mutually independent technology for the detection scheme. As the signal strength is less in field, the system uses a mobile node equipped with more sensitive equipment to reach the suspected area, collect signals and confirm the presence of explosives and thus provide an enhanced target tracking. The area can be divided into a number of small regions or clusters. Multiple sensors of varying type are deployed in such a way that the network can cover the whole region. All the sensed data is sent to the sink node for processing. For the easy navigation of mobile node, there is a steel rope or channel on the roof of the platform. The system can be extended to other public places such as airports, bus stations, parks, embassies, hotels etc. with slight design modifications.

The paper is organised as follows: Section 2 describes a brief review of the related works. Section 3 and 4 presents the detection system architecture and network architecture. The algorithms used in the system are described in section 5. Section 6 deals with the advantages of the system followed by the conclusion.

2. RELATED WORKS

In conventional systems, dogs and honey bees were used to detect explosives. But they have restricted attention span and are very expensive. So, various instruments have been developed. Several existing detection methods that can be utilized for remote

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explosive detection are mentioned in [4]. The development of explosive detection with MEMS technology was briefly reviewed in [5]. For commercial application of potential MEMS (Micro Electro Mechanic Systems) based explosive detectors, require high sensitivity and excellent selectivity. Here also standoff distance is a main problem to apply in open environments. The authors of [6] utilize terahertz technology for explosive detection. The system uses very low levels of non ionizing radiation to detect and identify objects hidden under clothing. Many chemical substances and explosive materials exhibit characteristic spectral responses at THz frequencies that can be used for threat object identification. This technique is able to sense through several layers of clothing with the help of safe non ionizing radiations. As the maximum standoff distance that can be achieved from this method is 1m, in an open environment it is difficult to apply this method.

Some of the stand-off methods currently developed is focused on chemical identification. The main challenge includes the distances from which effective detection can be conducted in presence of various interferences from environments. Bourzac, Katherine describes a method to detect explosive materials using magnetic sensors developed for use in the battlefield [7]. The National Institute of Standards and Technology (NIST) have developed magnetometer for detecting the presence of magnetic materials [8]. But it does not consider the information about the chemicals used in explosives and it cannot be applied to scenarios where more metallic presence is found. German researchers developed a sensor system [9] to monitor people carrying explosive in public places. The system consists of two separate sensor networks to find chemical properties and kinetic information of the person. They are using their own chemical sensors for the sensor network. The cost of developing such type of sensors is comparatively high. In the proposed design, the system uses already existing components for sensing purpose. As one type of sensor is not sufficient to detect the explosive presence, the proposed design utilizes more than one independent technology. Also the system allows to continuously monitoring the area without affecting the passengers going through the monitoring area.

3. DETECTION AND ANALYSIS

3.1 Sensors for explosive detection

An explosive material can be identified chemically, magnetically, thermally and electrically. As the area under study contains more metallic content it is very difficult detect the explosives magnetically. The proposed design utilizes the chemical and thermal properties of the material. The design combines imaging technology, optical technology and chemical as well as thermal identification techniques. As the main constituent of explosives is chemicals, we use vapour sensors for the chemical identification. It is not possible for the commercially available vapour sensors to collect vapours from a large distance. So we used an air collecting system to collect large volumes of air. A filter or concentrator is used to remove dust and other common components of air from the collected sample. Vapour sensor is connected to the mote using an interface board and it can transmit the sensed data for analysis. One of the commercially available vapour sensors is EMAX-5300 which is capable of detecting the presence of plastic and high-vapour-pressure explosives, including taggants. It can detect and identify minute traces of C-4, TNT, Dynamite, etc. The sensor is provided with RS-232 serial output port for remote control and monitoring. A set of image sensors are used to locate unattended objects. Theses image sensors will capture the pictures of the scene periodically and send to the image analyzing server to identify unattended objects. The system also uses a thermal imaging technique. Quantum cascade lasers and thermal imaging cameras are used for this purpose.

In this wireless sensor network, the nodes are sensing one sample per 60 seconds. In each 60 seconds, the nodes can sense data, transmit data, receives data or sleep. We assume that the maximum packet size in the network is 1024 bytes. The total energy consumed by the node is the sum of the energy required for transmission, reception and idle time. We calculated the life time by dividing the total energy provided by the battery by the total energy consumed during transmission, reception and idle modes.

3.2 System Model

Most of the common people in India are depending railways for travelling. Effective mechanisms to detect the presence of explosive contents are not yet employed in our railway stations. So the main focus of this work is the railway stations in India. The area to be monitored is equipped with multiple numbers of varying types of sensors. These sensing components are deployed in the roof and corners of the platforms. This is a multi phase architecture in which the preliminary phase will continuously monitor the area for the presence of explosive materials with the help of mutually independent techniques. If the strength of signal collected from the sensors is greater than a particular threshold, the system will immediately give warning to the security personnel through internet or mobile network. If the collected signal strength is less than the predefined threshold, the system will perform advanced sensing phase for the confirmation.

Preliminary phase

To monitor the presence of explosives, the system uses vision based method, chemical identification and thermal identification. All these methods are done in parallel in order to provide more precise results and to reduce number of false alarms. If the data collected using different techniques are conflicting, the system will confirm the suspect by employing an enhanced target tracking using a mobile node. Image sensors will periodically take pictures of the scene and send to the image analysing server. The background images of the test area are already stored in the server. By running the object identification algorithm, the system is able to find out unattended objects. If any unattended object is found, the area under that image sensor will be close monitored by initiating advanced phase operations for the confirmation of suspected object. There are another set of image sensors used to take videos of the scene continuously. The videos are stored in the database and can be used reference if any suspect occurred.

The concentration of explosive molecules may be small in the test environment. To get more concentrated vapors of the air, the system uses a vacuum system which will collect large volume of air from the test area. These air molecules are filtered using a concentrator and fed to a vapour sensor. From the concentrated air molecules, the vapour sensor can effectively find the chemical composition of particles present in that air sample. We are using a set of cheap quantum cascade lasers (QCL) to illuminate the objects in the area. These lasers are tuned to the absorption frequency of common explosives like RDX and TNT.

With the help of a thermal camera, the system will collect the spectrum. We can cluster the data into explosive region and nonexplosive region using PCA analysis.

To analyze the sensed data, the system uses two thresholds; a high threshold t_{high} and a low threshold $t_{low.}$ If the sensed data is greater than the high threshold t_{high} , it will give immediate indications to the security personnel's. If the comparison result is less than t_{high} and greater than t_{low}, it will initiate advanced phase operations for the confirmation of presence or absence of explosive material. If the calculated result is less than t_{low}, the system will ignore the data. Figure.1 gives the design details of the system.

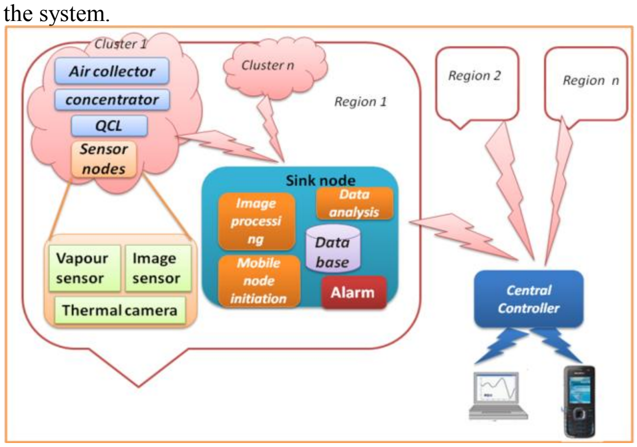

Figure. 1. The system design

Advanced phase

Whenever the sink node receives some suspicious data, the operations in advanced phase will be initiated. Then sink node initiates a mobile node which can move closer to the suspected area and can sense more accurate data. A special track made of steel rope is provided in the roof of the platform for the easy navigation of mobile node. This node will reach the suspected area and scan the area for explosives. The sensed data is immediately sent to the sink for verification of suspicious data. If the sink node confirms the presence of explosives, it will give indications to the security personnel through e-mail or internet or sms services so that they can take immediate actions. This mobile node can also be utilized, if any anonymous phone call about bomb threats is received by the officials. The system also provides a mechanism to track moving persons or objects carrying explosives.

4. TOPOLOGY AND ALGORITHM DESIGN

4.1 Topology design

There are multiple platforms in a railway station where each platform corresponds to a region. Each region is associated with a sink node and regions are divided into a number of clusters for effective communication. A central controller will coordinate the activities of all the sink nodes. Based on the communication range, the sensor nodes will generate clusters. The proposed design uses a regionalized clustering approach. In a cluster, there are multiple sensors of same type. The system will correlate the data coming from the sensors in a particular area, find the deviations of data and can ignore data accordingly. This allows the system to reduce wrong data processing. Also if any one of the sensor is not working properly, the remaining set of same type sensors can contribute data and can manage sensor faults. The following figure 2 illustrates the network topology.

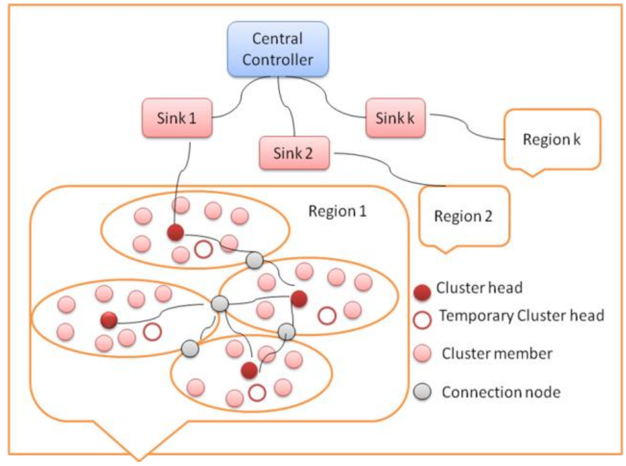

Figure.2. Network Topology

There are mainly four types of nodes in a cluster. These nodes are cluster member node, cluster head, temporary cluster head and connection node. Cluster members are low level nodes whose primary function is data sensing. A cluster member node contains different type of sensors. Each cluster is associated with a special node with more computational capacity called cluster head. The main functions of these nodes are to aggregate the data coming from cluster members, forward to sink node and coordinate the activities in the cluster. A small number of alternative cluster heads are provided to the network which can be shared among clusters to handle cluster head failures if any. Connection nodes in the network act as communication link between two clusters.

4.2 Algorithms

4.2.1 Regionalized clustering

The whole area is divided into a number of regions and each region is further divided into a set of clusters. The platform of the railway station can be considered as a region and each of which is associated with a sink node. There is a master node which will acts as the central controller of all these sink nodes. For each region, the cluster setup algorithm will elect one of the available special nodes as cluster head. Initially, in each cluster head, the administrator of the network will load the number of hops from that cluster head to the sink node. This is for computing the shortest route to the sink node from each cluster head. In this phase of the algorithm, the nodes in the network will exchange a set of messages. These messages are invitation message, response message, confirmation message, negotiation message, sink notify and acknowledgement.

Invitation message is a broadcast message sent by the cluster heads to invite other nodes in its communication range to create clusters. This message contains the ID of the cluster head. The nodes who receives invitation message will send a response message. This is an indication that the node is reachable from the cluster head and it is ready to join the cluster. The message includes the node ID, number of invitations, and the IDs of inviting nodes and corresponding signal strengths. Negotiation message is transferred between the cluster heads to compromise the number of cluster members and link nodes in each cluster. This maintains a minimum and maximum limit in the number of nodes in the cluster. Confirmation message is send by the cluster heads to confirm the membership in the cluster by specifying the ID of the cluster head. After receiving confirmation message, the cluster members will send an acknowledgement to the cluster head.

In the cluster generation process, cluster heads will broadcast an invitation message to all the neighboring nodes. The nodes which are in the communication range of the cluster head will receive this message. A node may receive invitation from more than one cluster heads. The nodes receiving invitation will send a response message to all the inviting nodes. If the signal strength of any of the invitation message is less then it will ignore the invitation otherwise send a response. The cluster head will store the details of response messages in a table. The nodes receiving invitation from more than one cluster head are the candidate of a connection node which is a bridge between the communications of two cluster heads. Using any one of the connection nodes, the neighboring cluster heads will communicate with each other to make an agreement between numbers of cluster members and connection nodes. The network design supports only at most two connection nodes between two clusters in order to avoid energy wastage of these nodes. Depending on the total number of cluster members of neighboring cluster heads, the extra connection nodes will be changed to cluster members of any one of the cluster head and update the cluster table. The cluster heads will send a confirmation message to all nodes in its cluster table. By receiving this confirmation message, the member nodes will store the ID of cluster head and send an acknowledgement to the cluster head. If the cluster head is not receiving the acknowledgement after the timeout period, it will retransmit the confirmation message.

All cluster heads in the network knows the number of hops to the sink node from that node. These cluster heads have to forward the aggregated data to the sink node. For fast and effective forwarding, the number of hops travelled by the packet should be less. We used Dijkstra's shortest path algorithm [10] to find the shortest path from each cluster head to sink node. It uses number of hops to the sink as metric of the algorithm. The shortest path information is added to the routing table of each cluster head and connection node. Sink notify message is the message exchanged between the sink nodes to indicate their status. After setting up of clusters, the actual communication between the nodes will take place. The messages can be synchronization message, data message, status message, mobile node initiation message or aggregated data message. Based on the type of message received the receiving nodes process the data, update itself and forward it if required.

4.2.2 Multilevel data aggregation and analysis

All the cluster members will collect data periodically and send to the cluster head. The main function of cluster head is to aggregate the data. There is multiple numbers of varying types of sensors in a cluster. Based on the timestamp, the cluster members will store the data from all type of sensors and create a vector. The number of such vectors in cluster heads will be different based on the number of sensing nodes in a cluster. It will compute the correlation between each vector using the following Karl Pearson's correlation coefficient.

$$r = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{\sqrt{n\left(\sum x^2\right) - \left(\sum x\right)^2}\sqrt{n\left(\sum y^2\right) - \left(\sum y\right)^2}} \quad (1)$$

If r >= 0.8 or r < = -0.8, then there is a strong correlation between the vectors. So it is not required to send all the incoming data, only one vector is sufficient. This will reduce the communication cost of the system. If the correlation coefficient is less than 0.5, it is required send the differing vectors. Cluster head will add a time stamp and forward the aggregated vector to the sink by selecting the shortest route in the routing table. Analysis of the aggregated data is done by the sink node. The chemical signatures of already known explosives are stored in the database of sink node. The received aggregated data is compared with the signatures stored in the database. If the received data is less than the low threshold t_{low},, the system will ignore the data. If the incoming data is in between t_{low} and high threshold t_{high}, the sink node will initiate a mobile node for the confirmation of explosives in the suspected area. If the data is greater than t_{high}, then the system immediately give indication to the concerned people.

4.2.3 Advanced sensing using mobile node

If the sensed data is in between t_{low} and t_{high}, , we cannot surely say the suspected area contains an explosive and cannot disseminate an alarm. It may be an erroneous/noisy data. In this situation, the system uses an enhanced target tracking phase to confirm the presence or absence of explosive and to avoid wrong alarms. The sink node will localize the area by executing the localization algorithm. The area under monitoring is equipped with a steel rope on the roof. The sink node will initiate a mobile node which can traverse though this path and can reach the area under suspect. The movement of the node is automatically controlled. The position calculating function in the node calculates the distance to the target and slides through the predefined path. Also it can communicate with sink node and nearby cluster heads for finding the target. This node can carry out the detection process more close to the target. The sensed data will be immediately send to the sink node for the confirmation of suspected target.

4.2.4 Localization of suspected area

In case of suspicious data, the sink node will activate a mobile node for the confirmation of suspected object. The distance and number of hops to all cluster heads from the sink node is stored in the database of the sink node. The sink node will look up the distance to the corresponding cluster head from where the suspected data is obtained. As the mobile node is moving with constant speed, the sink node will calculate the time to reach the suspected cluster head from the distance and speed parameters. Then it will initiate the mobile node intimated with the location information. Also it sends a message to the cluster head in the suspected area to indicate that, the mobile node has been initiated and it will reach the cluster head with in t seconds. The cluster head knows the location of static cluster members. It checks the previous packets and finds the coordinate position of the sensor nodes from which the suspicious data was obtained. Then it uses triangulation technique to find the approximate location of suspected target. After t seconds, the cluster head will broadcast a message with the location information, which can be received by the mobile node. By receiving this message, the mobile node is able to go more close to the suspected object. It will sense the data forwards to the sink node and provide a better tracking mechanism.

4.2.5 *Alarm dissemination phase*

If the presence of explosive material is confirmed by the sink node, then the system will provide an early warning to the concerned persons. For the indication of explosive material presence, it uses existing mobile network and internet. The system will automatically give sms alerts and e-mail alerts to the important security officials. The authorized persons can view all the sensed data from the sensor network in the internet in real time. Depends on the variations in the sensed data, the officials can take immediate actions. In the case of threat messages or calls, the administrator can configure the system to change the sampling period and threshold limits so that the system can provide improved results.

4.2.6 *Time synchronization*

In a sensor network, there may be propagation delay of the packets due to some environmental factors. The sensors have to coordinate their actions for the aggregation of data. If there is no time synchronization, the aggregated data may be an erroneous. Each sensor node is associated with a clock based on its oscillator frequency. Due to atmospheric conditions such as temperature, pressure, there may be slight difference in the oscillating frequency and in turn result in a drift from original clock. But the network protocol requires a common clock to avoid erroneous data. In The system, the clock in all the nodes of the network is synchronized with respect to the clock of sink node. Sink node uses a spanning tree algorithm to find connected components of network graph. It will send a synchronization message with current clock time to the cluster heads.

To handle the difference in clock value due to the delays in the network, we calculated an estimate of delay of packets. Here we considered only the transmission delay and propagation delay. Also it is assumed that the distance between two communicating nodes is a constant *r*. The propagation delay between two communicating nodes depends on the distance between them and the signal propagation speed. The propagation delay (*prop_delay)* is computed as the ratio of distance between nodes to the speed of light. Also we calculated the transmission delay, *trans_delay* as the ratio of number of bits to the transmission rate.

$$\text{prop\_delay} = r / c. \quad (2)$$

$$\text{trans\_delay} = \text{packet length} / \text{transmission rate}. \quad (3)$$

$$\text{delta} = \text{prop\_delay} + \text{trans\_delay}. \quad (4)$$

The cluster heads knows the number of hops required to reach the sink node. Whenever the cluster head receives such a synchronization message, it will multiply the number of hops and the *delay* factor to calculate propagation delay. This propagation delay will be added to the incoming clock data and the local time will be updated. After the synchronization of cluster heads, the will create a synchronization packet with updated data and broadcast to cluster members. They will add the delay factor and update the clock time.

4.2.7 *Secure data transmission*

As the network deals with more sensitive data, it is required to prevent unauthorized capturing of data flowing through the network. To provide security to the data transmission, we are using frequency hopping [11]. The available bandwidth is divided into a number of bands. The network operates between 2400MHz and 2483.5 MHz. It is divided into 12 nonoverlapping channels. The channel allocation algorithm randomly selects a particular channel and used for transmission. The receiver is also using the same algorithm and seed for the generation of frequency. As the algorithm randomly selecting the channel, it is very difficult for the intruder to find the sequence of frequencies used for transmission and thus provides security for the transmission.

4.2.8 *Tracking of persons carrying explosives*

A sink node is associated with each platform of the railway station and these platforms are divided into small clusters. At a time instant one cluster cluster_i reports a deviation from normal value and after a short period of time, another cluster cluster_j reports deviation, the system will closely examine the clusters showing positive result. From this trajectory the sink can identify whether the explosive presence is moving or not. Then the sink node will activate all cameras and give alert messages to all other sinks. The location information of all cluster heads are statically stores in the data base of sink node. By looking up the database using the ID of cluster head from which the suspected data was obtained, it is easy to find the location.

5. PERFORMANCE TESTING

To implement the system, we used the operating system called TinyOS, MicaZ motes and ZigBee technology. With the help of the components and interfaces of TinyOS, the network of sensors will communicate with each other. The sensor nodes and gateways are using CC2420 RF transceiver. Each cluster member in the system can sense the data and communicate to higher level nodes. Also they can receive synchronization messages and other control messages from higher level nodes in the hierarchy. The transmission and reception of the messages are through MicaZ mote embedded with ZigBee compatible RF transceiver .The communication uses frequency between 2400MHz and 2483.5 MHz. MicaZ expansion connector is used to connect to other sensors, data acquisition boards and gateway. We employed MIB600CA to connect the wireless network to wired network for streaming the sensed data to the internet.   To evaluate the performance of the proposed system, we simulated the functionality in National Instruments Lab View – Real Time software.

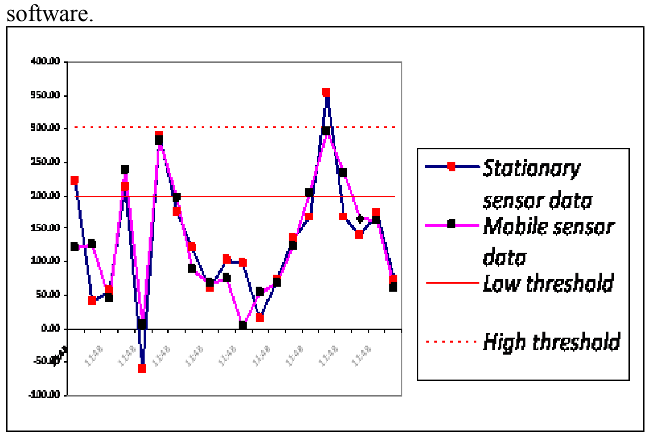

Figure .3. Difference in the data gathered by stationary and mobile sensor in a low noise environment.

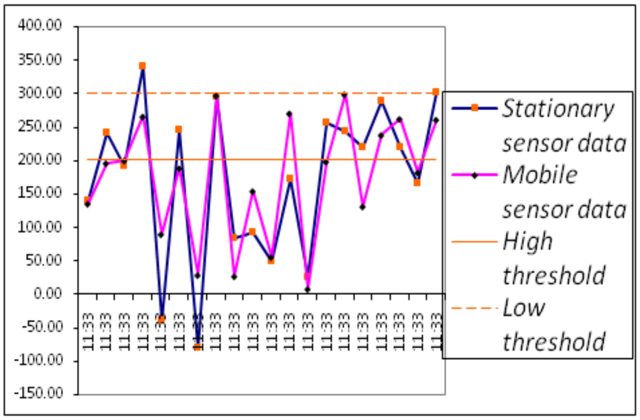

Figure.4. Data collected by stationary and mobile sensors in high noise environment.

The data coming from each type of sensor is plotted and analyzed against the threshold levels. Due to atmospheric noise, there may be variation in the collected data and it may lead to wrong alarms. To reduce number of wrong alarms, the system uses a confirmation phase where a mobile node can move closer to the suspected object and can sense data. If the degree of noise is less, the data sensed using stationary sensor and mobile sensor are almost same as shown in figure 3. We assumed that the noise in the stationary sensor data follows a Gaussian distribution. As the degree of noise increases, the data collected using stationary sensors are mixed with random values. This may cause wrong alarms; explosive presence may be interpreted as explosive absence and vice versa. Mobile nodes can sense the data from the nearer regions of suspect and the accuracy of the sensed data can be improved. This will reduce number of false alarms. Figure 4 gives the difference between the data sensed using stationary sensor and mobile sensor. The comparison result shows that the use of mobile node in the system significantly reduces the number of false alarms.

6. ADVANTAGES

The main advantage of this system is that it will continuously monitor the presence of explosives and take appropriate decisions with minimal human intervention. Also the detection process does not affect the routines of passengers present in the area and the system is hidden from them. This can be employed in any wide and open areas with slight design modifications. As the system uses a confirmation phase and data from more than one mutually independent technique, the probability of wrong alarms are significantly reduced. With the help of frequency hopping the network provide security to the data available in the network. The security officials need not visit the site for getting details; instead it is available in the network. The system provides facilities for authorized persons to view the sensed data through the internet in real time and to get security alerts through e-mail or mobile phone.

7. CONCLUSION AND FUTURE SCOPE

Using wireless sensor network technology, the proposed system will monitor the environment for explosive contents and will give indications to the authorized persons in case of positive results. This is a wide area, continuous, remote monitoring system with minimal human involvement in the detection process. The system can be deployed to any public places such as railway stations, airports etc. for the safety of general public and infrastructure. The system makes use of a set of orthogonal techniques with multiple sensors of varying types to maximize the accuracy and reliability of the system and to reduce false alarms. Enhanced target tracking is achieved by using a confirmation phase with the help of a mobile node which can traverse the whole area through a predefined path. If the system confirms the presence of explosives, the concerned people are informed via the existing mobile network and internet. There may be performance degradations in outdoor environment due to atmospheric noise. The future development will concentrate in decreasing the effect of noise in the system.

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