Earthquake Early Warning System

[1]T. Sudarvizhi and [2]D. Jayasutha,
[1]Research Scholar, [2]Assistant Professor,
[1,2]Computer Science and Engineering Department,
TamilNadu College of Engineering, Coimbatore, Tamil Nadu, India.

Abstract: High-speed trains, carrying high social and commercial value, travel at a speed over 250km/h, thus any damage to tracks would cause severe loss. Detecting events which can cause track faults is important to the safety of high-speed railway systems. Railways, crossing the vast area of plains and mountains, are vulnerable to earthquakes which can damage tracks with destructive forces. Hence there arrives a need for Earthquake Early Warning (EEW) system provides advance information of the estimated seismic intensities and expected arrival time of principal motion. These estimations can be obtained by prompt analysis of the focus and magnitude of the earthquake using wave form data observed by seismographs near the epicenter. However, conventional EEW system cannot offer satisfactory alarms for high-speed railway systems. Therefore, it is necessary to develop an EEW for high-speed railways (HREEW).One of the key issues in designing an HR-EEW system is how to offer timely alarms to trains under certain constrains, such as budget limitation and geological restriction. We propose HR-EEW systems based on wireless sensor networks(WSNs).In this proposal, we take a close look at deploying wireless sensor nodes in HR-EEW systems. We target at solving the minimum cost deployment problem while guaranteeing that any earthquake in a seismic district can be timely reported by k sensors.

Keywords: *Wireless Sensor Network, Earthquake Early Warning, High Speed Railway- Earthquake Early Warning, Railway Control Center.*

I. INTRODUCTION

A. Wireless Sensor Network (WSN)

"A new class of network has appeared in the last few years the so called WSN These network consists of individual nodes that are able to interact with their environment by sensing or controlling physical parameter, these nodes have to collaborate to fulfil their tasks". A wireless sensor network(WSN) of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location. The more modern networks are bi-directional, also enabling *control* of sensor activity. The development of wireless sensor networks was motivated by military applications such as battlefield surveillance; today such networks are used in many industrial and consumer applications, such as industrial process monitoring and control, machine health monitoring, and so on. The WSN is built of "nodes" – from a few to several hundreds or even thousands, where each node is connected to one (or sometimes several) sensors. Each such sensor network node has typically several parts: a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors and an energy source, usually a battery or an embedded form of energy harvesting. A sensor node might vary in size from that of a shoebox down to the size of a grain of dust, although functioning "motes" of genuine microscopic dimensions have yet to be created. The cost of sensor nodes is similarly variable, ranging from a few to hundreds of dollars, depending on the complexity of the individual sensor nodes. Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and communications bandwidth. The topology of the WSNs can vary from a simple star network to an advanced multi-hop wireless mesh network. The propagation technique between the hops of the network can be routing or flooding.

B. Earthquake Early Warning (EEW)

Earthquake is a destructive source of geologic change; railway engineers try their best to build railway lines far away from seismic districts, which are prone to have earthquakes. However, parts of railways are adjoined to or cross with the seismic districts inevitably because the seismic districts are widespread on the continental plates. If high-speed trains are warned before an earthquake strikes the rail, taking actions such as slowing down the trains to a safe speed can avoid a lot of loss. Earthquake early warning systems (EEW), are developed to offer warnings to critical facilities, such as nuclear plants, and the general public before an earthquake strikes[11][5]. Different from cities and nuclear plants which are considered as points geographically, railways are regarded as lines. High speed trains can be at any place on the lines when the earthquake happens. As a result, warnings offered by conventional EEW system are always too late for high-speed railways. That is why Japanese made special changes to EEW for their Shinkansen by offering a fast but unprecise alarm[9]. With the improvement of advanced techniques and reducing cost of hardware, it is possible and necessary to develop EEW systems customized for high-speed railway(HR-EEW). HR-EEW can not only report earthquake in the disasters, but also carry out geological hazard monitoring work along the railways which improves safety of railway systems. We propose a HR-EEW system based on wireless sensor network (WSN). In the past decade, WSNs have been developed and deployed in many domains such as environmental monitoring [19], structural health monitoring [7], volcano monitoring [1] because of their low cost, simple maintenance and easy deployment. By equipping the sensor node with seismometers, we deploy a WSN to detect earthquakes and report the earthquakes to the railway control center and the trains (see Fig.1). In our previous work [10], we developed a long-range communication hardware module. By real experiments in a high-speed railway monitoring application in Nanjing, Jiangsu province, China (part of Jin-Hu High Speed Railway Monitoring project), we validated the feasibility of using wireless sensors to carry out long range-communication in outdoor environment along the high-speed railways, which is prerequisite for HR-EEW system. In this paper, we focus on how to deploy wireless sensor nodes under budget constrain and performance requirements of HR-EEW systems. In this paper, we take the first steps to discuss minimum cost sensor node deployment problem in HR-EEW system. We derive a necessary and sufficient condition for the problem. We demonstrate that, if a critical area is covered by the WSN, the HR-EEW system will satisfy the predefined performance requirement. After that, we discuss the characteristics of the critical area and develop an optimal sensor deployment algorithm for the line topology, and then extend our algorithm to the general topology.

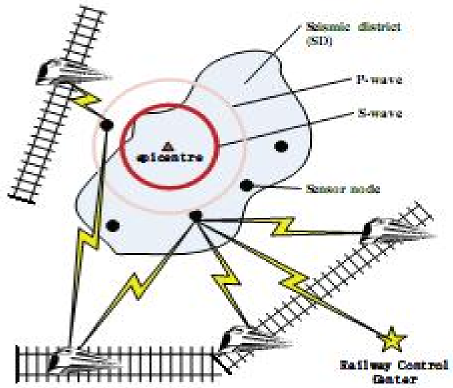

Figure 1: An illustration of HR-EEW.

C. Piezo electric sensor

Piezoelectric sensors have proven to be versatile tools for the measurement of processes. They are used for quality assurance, process control and for research and development in many industries. Although the piezoelectric effect was discovered by Pierre Curie in 1880, it was only in the 1950s that the piezoelectric effect started to be used for industrial sensing applications. Since then, this measuring principle has been increasingly used and can be regarded as a mature technology with an outstanding inherent reliability. It has been successfully used in various applications, such as in medical, aerospace, nuclear instrumentation, and as a tilt sensor in consumer electronics [1] or a pressure sensor in the touch pads of mobile phones. In the automotive industry, piezoelectric elements are used to monitor combustion when developing internal combustion engines. The sensors are either directly mounted into additional holes into the cylinder head or the spark/glow plug is equipped with a built in miniature piezoelectric sensor.[1] The rise of piezoelectric technology is directly related to a set of inherent advantages. The high modulus of elasticity of many piezoelectric materials is comparable to that of many metals and goes up to 10^6 N/m² Even though piezoelectric sensors are electromechanical systems that react to compression, the sensing elements show almost zero deflection. This is the reason why piezoelectric sensors are so rugged, have an extremely high natural frequency and an excellent linearity over a wide amplitude range. Additionally, piezoelectric technology is insensitive to electromagnetic fields and radiation, enabling measurements under harsh conditions. Some materials used (especially gallium phosphate [2] ortourmaline) have an extreme stability even at high temperature, enabling sensors to have a working range of up to 1000 °C. Tourmaline showspyro electricity in addition to the piezoelectric effect; this is the ability to generate an electrical signal when the temperature of the crystal changes. This effect is also common to piezoceramicmaterials. Gautschi in *Piezoelectric Sensorics* (2002) offers this comparison table of characteristics of piezo sensor materials vs other types:[2]

Principle	**Strain Sensitivity [V/με]**	**Threshold [με]**	**Span to threshold ratio**
Piezo electric	5	0.00001	10,00,00,000
Piezo Resistive	0.0001	0.0001	25,00,000
Inductive	0.001	0.0005	20,00,000

Capacitive	0.005	0.0001	7,50,000
Resistive	0.000005	0.01	50,000

II. RELATED WORK

EEW systems have been implemented and deployed in japan[6], Taiwan[15], mexico[4] and united states[17]. These systems are designed to protect the cities and important facilities. Because the warnings from these conventional systems are too late for many facilities such as shinkansen, Urgent Earthquake Detection and Alaram System (UrEDAS) [9] is proposed. A few researches have been taken in deploying wireless sensor network in EEW systems. [8] studies the effect to the wireless communication caused by continuous earth shaking. WSNs are proposed to detect Earthquake using the phenomena in the ionosphere and magnetosphere preceding earthquakes[20]. In [14], a power-efficient WSN is developed to continuously monitor seismic vibrations. Our system is not strictly adhere to current earthquake techniques. It can be smoothly updated with future improvement of earthquake detection techniques.

III. SYSTEM OVERVIEW AND PROBLEM STATEMENT

We planned to do the *deployment scheme* (sensor number and locations, etc.) according to the seismic district information, railway information and certain predefined performance requirements of the HR-EEW system. Then we deploy sensor nodes according to the deployment scheme. This sensor generates a warning report that is transmitted to the railway infrastructure through the WSN. After that, the infrastructure sends the report to the trains running in the area that may be affected by the earthquake. When a train receives the report, it takes emergency responses such as braking. Meanwhile, the warning report is also sent to the railway control center which adjusts the train schedules.

IV CRITICAL CONDITION

In order to find a minimum cost deployment scheme. We need to clarify the relationship between a deployment scheme and the performance it can achieve. In this section, we first work out the relationship between a deployment scheme and its performance. After that, we derive a critical condition which largely reduces our workload on developing deployment scheme.

A. Performance of A Deployment Scheme

Definition 1*:* When an earthquake happens at epicenter E, the sensor node at S generates a warning report after the Pwave arrives at S. The damage-prone point P receives this report at time tw. The destructive S-wave arrives at P at ts. We call the time interval (ts −tw) *earthquake early warning time* (EEWT) for (E,P, S). Denoted by eewt (E,P, S).

Definition 2: Given an epicenter E, a damage-prone point P and a predefined time performance requirement T_, *feasible location area(FLA)* for (E,P, T_) is an area where all points in this area are feasible locations for (E,P, T_). Denoted by fla(E,P, T_).

The feasible location area determines the area where feasible locations for (E,P, T_) exist.

Definition 3: Given a railway R and a predefined time performance requirement T_, the T_-R-*coverage* of S is the set of all points E, where E is T_-reported to R. Denoted by C(S,R, T_).

Apparently, the seismic district decides whether a point in the T_-R-coverage of S is a possible epicenter. For a HR-EEW system, only the coverage on possible epicenters is useful. We define effective T_-R-coverage as follows.

Definition 4: Given a possible epicenter group EG, a damage-prone point P and a predefined time performance requirement T_, the *effective* T_-R-*coverage* of S is the set of points E EG where E is T_-reported to R. Denoted by EC(EG, S,R, T_).

When there is no ambiguity in the context, we denote EC(EG, Sj,R, T_) as ECj . between the sensors and the epicenter are different. So are the distances between the sensors and P. As a result, the reports are not received by P at the same time. We define combined performance to describe the performance of a HREEW

Definition 5: Given an epicenter E and a Railway R, combined performance k-T of a HR-EEW system means k sensor nodes report an earthquake at E with an EEWT no less than T to all points on R. In other word, E is T -reported to R by k sensor nodes in the HR-EEW system.

Theorem 1: Given SD and R, the HR-EEW system guarantees the predefined combined performance k-T_, if and only if all vps in RV B(R, SD) are T_-reported to R by at least k.

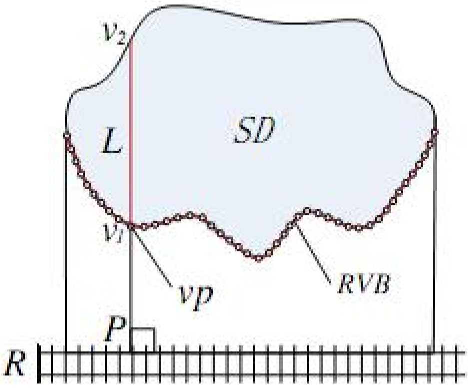

Figure 2: Illustration of Vp and Vb.

B. RVB and Critical Area

Let L be a line which is perpendicular to the railway line R and intersect with R at P(see Fig.2). if L intersects with SD at the line segment v_1v_2, we let vertical mapping point vp(L,SD) be v1 or v2 who is closer to R. let the points on line segment v_1v_2 be a group G of epicenters, then vp(L,SD) is E_(G,P). if L moves along the direction of R, the resulting vps from from a Representative Vertical-Mapping Border RVB(R,SD). The critical condition is represented as follows.

Theorem 1: Given SD and R, the HR-EEW system guarantees the pre defined combied performance k-Te, if and only if all vps in RVB(R,SD) are Te-reported to R by at least k sensor nodes.

V. DEPLOYMENT METHODOLOGIES

A. Straight Line RVB

When RV B is a straight-line segment, the effective T_-Rcoverage of a sensor location S is the intersection between C(S,R, T_) and this straight-line segment. This effective coverage is continuous.

Lemma 2: The effective T_-R-coverage of a sensor location on a straight line segment is continuous.

Proof:Due to page limitation, please refer *Optimal deployment algorithm:* We first define a concept of *skyline*. It indicates the coverage status of the deployment. Our algorithm starts from vp1 and iteratively moves the skyline to the end point vpn. *Definition 6:* For a k-T_ deployment, *skyline* is a set of numbers (c1, c2, . . . , cl, . . . , ck), where cl indicates (vp1, vp2, . . . , vpcl) are l-T_-reported and (vpcl+1, . . . , vpn) are not l-T_-reported. The definition of skyline implies c1 ≥ c2 ≥ . . . ≥ ck. In other words, an epicenter is impossible to be l-T_-reported but not i-T_-reported for i< l. Let the continuous effective coverage ECj represented as (bj, ej) where bj and ej are the minimum index number and the maximum index number of vps in ECj respectively. We assume S = S1, S2, . . . ,Sm are sorted by bj in ascending order. We process the sensor selection in this order. Let CDi(c1, c2, . . . , ck) denote the set of deployments which choose sensor locations from (S1, S2, . . . , Si), these deployments induce a skyline(c1, c2, . . . , ck). Let CDmini (c1, c2, . . . ,ck) be the minimum cost deployment among CDi(c1, c2, . . . , ck). Let cdmini (c1, c2, . . . ,ck) be the minimum cost of CDmini (c1, c2, . . . , ck). We have the following recursive relation. cdmini (c_ 1, . . . , c_ j−1, ei, c_ j, . . . , c_ k−1) = minc_ k<bi cdmini−1 (c_ 1, . . . , c_k) + sci,cdmin1 (c_1, . . , c_j−1, ci, c_j, . . . , c_k−1)_(1)Equipped with the recursive relation, we build a direct acyclic minimum sensor node problem is transformed to a short path problem from CD0 to CDe for the constructed DAG. here are many classic algorithms for this kind of problem. The algorithms of this short path problem are deterministic. If there is no path from CD0 to CDe, there is no feasible solution for the original problem. We develop Optimal Deployment () algorithm for this specified scenario. This algorithm has two parameters. S is a set of feasible locations. CS is the effective T_-R-coverages of sensor locations in S. The effective T_-R-coverage for a specified sensor location Si is obtained by checking all the vps in RV B which are T_-reported to R by Si. In algorithm Optimal Deployment(), we first check whether the effective cover ages are all continuous. This is the prerequisite for this algorithm. Secondly, we construct a DAG and solve the shortest path problem from CD0 to De in the constructed DAG. Finally, we visit the shortest path and put all the nodes in the path into SL. The complexity of the algorithm is O(m m! m−k)!k!). In the traditional EEW systems, k is typically Seismic hazard map for the area near JingHu high-speed railway.

B. General RVB

For a general RV B, vps vary in the 2D space. The effective coverages of RV B are not continuous for some sensor nodes. However, we find there is only a little proportion of sensor nodes whose coverages are not continuous. The reason for this phenomenon is that after reducing the representative epicenters, the total number of representative epi centers is small and the remaining vps always crowd in the area closer to the railway line. The probability for a sensor to gain a non-continuous effective coverage is low. Based on this observation, we cut the small segments and keep the longest continuous coverage segment. Then the general scenario is reduced to a specified scenario which can be solved by algorithm OptimalDeployment(). We develop algorithm EEWTaware- H() for this method.

First, we check the effective coverage for every sensor location Si. If ECi is not continuous, we find the longest continuous segment EClong and replace ECi with EClong. Then we call OptimalDeployment() to calculate the optimal solution for the adjusted coverage data. We notice that the sensor nodes which violate the continuous condition are always far from the railway line, their deployment cost are higher.

Thus these sensor nodes are unlikely to be selected in the optimal solution. We also Introduce a greedy-based algorithm EEWT aware G() for fast solutions. We define *effective Cover number* as the number of vps which are not k-T_-reported in the effective coverage of a sensor location. Intuitively, effective cover number indicate the effect if employing this sensor location. Maybe the number of epicenters in a coverage is large, but most of these epicenters are k-T_-reported in previous elections.Thus the effective cover number of this location is small and selecting this location contributes little to the effort of satisfying the combined performance k-T_. We define effective unit cost as sci divided by effective cover numbers.

VI. EVALUATION

The performance of our proposed system is evaluated with Schema Cost, Distribution Space Analysis. Here the Schema cost is the time taken to deploy the sensors with minimum numbers and with shortest path to the RCC. We define *Distribution Space* as the average space between the sensors comprising the predefined performance requirements. Bothe these parameters are evaluated by varying the number of sensors deployed across the seismic district in the scale of 10 nos. This simulator has been developed in such a way so that it can support or work with different kinds of deployment algorithms. The proposed simulator has the ability to generate different scenarios with varying sensors and railway tracks so as to allow users to use the same scenarios when comparing different algorithms. iteration of algorithm EEWT-aware-G(), we choose the sensor location which has the minimum effective unit cost among all unselected locations in S. For each vpi in RV B, we create a cover number cni to record the number of times vpi is T_- reported. When Sj is selected, we increase cni by 1 for all vpi∈ECj .

CONCLUSION

In this paper, we took the first steps to explore an HREEW system on WSN. We investigated the important deployment problem thoroughly and find the critical condition underneath. Based on the critical condition, we proposed novel algorithms to derive solutions for the problem under different scenarios. Our extensive simulations using both real world geographic information and synthetic data show our methodology can solve the problem effectively.

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