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Smart Highway System to Ensure Safety Services Using Wireless Sensor Network

[1]Sajib K. Mistry, [1]R. Karim, [2]K. Sakib and [1]M.H. Kamal
[1]Department of Computer Science and Engineering, [2]Institute of Information Technology,
University of Dhaka, Dhaka, Bangladesh

Abstract: Modern technologies have become an evident solution to reduce undesirable highway casualties and fatalities. The convergence of Wireless Sensor Network (WSN) and telematics creates the opportunity to develop cost effective and easily manageable highway safety services for developing countries. In this study, the architecture of a Smart Highway System (SHS) is designed using WSN. The SHS increases highway safety by early collision warning, detecting violation of speed limit and automatic reporting of unnatural events like road accidents. The network for the SHS is self-constructed using the proposed algorithm automatic route initialization, which inherently detects sensor node failures and increases system stability by re-constructing the network. To construct the SHS, prototype sensor architecture is designed to detect velocity and moving direction of vehicles using a noise free weight threshing technique in a single package. The sensor readings and warning signal of base station propagate through the network using the data model of the TinyDB and reverse modification process of Directed Diffusion. An exhaustive simulation was performed to analyze the effectiveness of the system and to find relationship among hop-counts of the network, average distance of the deployed sensor nodes and the highest manageable vehicle velocity by the SHS. The simulation result shows that if number of hop-counts increases then the spacing among the sensor nodes on the roads should be increased. The correctness of the proposed SHS system is exemplary to develop new applications using WSN for developing countries.

Key words: Kalman filter, sensor networks, TinyOS, TinyDB, Directed Diffusion

INTRODUCTION

Road traffic accidents, injuries and fatalities have been creating concern to the community in the world. Although, the world is becoming modernized day by day, use of technologies to ensure highway safety is very limited in developing countries. World Report on Road Traffic Injury Prevention has estimated that worldwide 1.2 million people are killed in road accidents each year and as many as 50 millions are injured (Hoque, 2006). The road safety situation in Bangladesh has been deteriorating with increasing number of highway casualties due to lack of technology in highway road safety. Road accidents (mostly in highways) are costing about US $ 800 million (nearly 2% of GDP) annually (Hoque, 2006). It stands to reason that a cost effective highway road safety system could have significant impact on the economy of developing countries.

Timothy *et al.* (2007) showed that 40% highway crashes at rural intersection points are mostly caused by high speed vehicles as drivers make wrong decisions from the geographical viewing obstruction at intersections. The driving misinterpretation causes the highest highway fatalities in different types of roads like intersection, curved and bumping etc. The Driver Assistance System (DAS) in Intelligent Transportation System (ITS) can reduce highway casualties by propagating early collision warning signals to driver (Hoh *et al.*, 2006). The architectures of Global Positioning System (GPS) based traffic monitoring and alarming systems are proposed by Hoh *et al.* (2006) and Anurag *et al.* (2008). The GPS receiver costs around $250 per vehicle (U.S. NEWS, 2009) that is a costly amount in developing countries. To build a GPS based automated system, every objects in the system need to be equipped with this costly GPS receiver. This is not feasible to underdeveloped or developing countries considering their economic backbone. The uses of optical systems like camera monitoring or image processing in detecting and classifying vehicles to increase highway safety are described by Panos (1991) and Wen *et al.* (2006). Due to complex image processing algorithms, these systems tend to increase the network latency in the warning systems (Timothy *et al.*, 2007). To avoid implementation constraints of GPS and optical systems, Sung *et al.* (2007) proposed the early collision warning system at curved road using WSN. Similarly, Timothy *et al.* (2007) designed a highway safety system at intersections using WSN. The cost effectiveness,

Corresponding Author: Sajib K. Mistry, Department of CSE, University of Dhaka, Dhaka, Bangladesh

accurate sensing and survival ability in harsh condition make WSN a winner over GPS and optical systems (Pathan *et al*., 2006). The system architecture (Sung *et al*., 2007) creates congestion in the network as the sensor nodes need to be synchronized with respect to time. The warning system architecture (Timothy *et al*., 2007) only works for intersections and can not be scaled for other types of road structures. In this study, a Smart Highway System (SHS) is proposed that works in different road structures like intersection, curved and bumping roads. Here, the sensor nodes need not be synchronized to create warning signals and the time based operations like predicting possible collision time etc. are performed in the base station. The proposed system also includes new safety services apart from giving warning signals. The new safety services include detection of speed limit violation, detection of unnatural events like road accidents and automatic reporting of all events. This will help to analyze highway safety situation and create new safety policies.

The SHS is designed for developing countries like Bangladesh. It is designed with three components: sensors, indicators and a base station. Sensors sense vehicles position and velocity and send the data to the base station. Using the cumulative data, the base station takes decision on the safety situations and fires appropriate indicator and other safety equipment (for example, radio signal) if needed. The SHS uses a proposed algorithm automatic route initialization to construct a tree based sensor network. The algorithm detects sensor node failure automatically by checking missing links in the collected reply messages termed s-message from sensors. The algorithm also tries to reconstruct a new tree from the existing active nodes if node failure occurs. The link layer protocol for the SHS is RMAC (Du *et al*., 2007) which shows better performance than traditional wireless MAC protocols (for example IEEE 802.11 etc.) and duty-cycle MAC protocols (for example S-MAC etc.) (Du *et al*., 2007). The propagation of sensor readings from sensors to the base station and warning signal from base station to indicator is designed with the fusion of TinyDB (Madden *et al*., 2005) and Directed Diffusion (Intanagonwiwat *et al*., 2003). The global table for the SHS is analogous to the global table of TinyDB on which all messages are constructed. The reverse process of Directed Diffusion is used to propagate the root initialization message (r-message), sensor reply message (s-message), sensor reading message (v-message) and warning message. The use of TinyDB and Directed Diffusion ensures the energy efficiency of the system (Madden *et al*., 2005). Because of the lack of full services from currently available sensors, according to the specification of the SHS system, prototype sensor architecture is proposed to detect vehicle velocity and moving direction. To predict time of possible highway collision, the well known linear Kalman filter with physics law of motion is used.

Using random distribution of sensor nodes and different car velocities with random acceleration in the simulation, it was tried to prove that collision warning is delivered to a driver in time to take appropriate measures for avoiding the collision in the system.

This condition pushed the simulation research to find a relationship among hop-counts of the network, average distance of the deployed sensor nodes on the road and the highest manageable vehicle velocity by the SHS. The relationship states that if more sensors are deployed in a fixed area, the distance among detector sensors should be increased when the highest car velocity is fixed. If the highest velocity of a car increases, the distance among detector sensors need to be increased to make the system work correctly.

MATERIALS AND METHODS

The background of TinyOS, TinyDB and Dirrected Dif- fusion is discussed in this section. TinyOS is the operating system for sensor motes. The size of TinyOS is around 4 KB and only static memory allocation is enabled (Heidemann and Govindan, 2005). TinyDB is a query processing system with a SQL-like interface for extracting information from a network of TinyOS sensors. It remedies the implementation of embedded NesC codes for the TinyOS. Madden *et al*. (2005) creates this energy efficient and data centric query processing for WSN. The power efficiency of TinyDB is discussed by Madden *et al*. (2005). The use of tiny aggregation in TinyDB causes great network efficiency in multi-hop networking (Madden *et al*., 2002). Directed Diffusion is a data centric routing protocol for WSN where the tracking interest propagates from the sink node and a gradient sets up along the source node with a reinforcement process (Intanagonwiwat *et al*., 2003).

Sung *et al*. (2007) proposed an early collision warning system for curved roads. A field test was performed in (Sung *et al*., 2007) by specifying a fixed dangerous area and three sink nodes having a distance of 50 m each. The test shows that warning message comes to the indicator sensor when the vehicles traveling at 100 km h^{-1} are 147 m apart from the dangerous area (Sung *et al*., 2007). Timothy *et al*. (2007) proposed architecture for early collision detection at intersection point. The architecture takes into account driver's reaction time, rate of deceleration, maximum possible velocity to determine the distance between the last node and the intersection point. The system deploys magnetic sensors that detects car from the change in magnetic field of sensors. The simulation result by Timothy *et al*. (2007) showed that 5 nodes separated by 10 m were 96% successful on crash prediction on either constant velocity or acceleration.

Overview of the proposed smart highway system: It is well known that driving error is the main cause of road accidents. Here, we assume that all accidents take place because of driver's misinterpretation about approaching vehicles. To reduce accident we need to detect the collision point early and must carry out signals to the vehicles operating in the accident scenario. The technology of WSN can create safety services to the highways. The proposed SHS with WSN motes are designed with three components: vehicle detector/ indicator sensor, information passing sensor and a base station/sink node. Vehicle detector sensors and indicator are placed on the road. The information passing sensors and base station are placed besides the roads. The base station receives vehicle information through deployed sensors and takes decision on activation of three safety services: early collision detection, velocity limit violation and detection of unnatural events. This decision signal also travels in the WSN network and gives early warning and other services.

Description of the proposed smart highway system: In this study, the implementation details of the SHS is discussed.

Sensor architecture for the proposed smart highway system: There are different types of sensing technologies available to detect various traffic parameters such as speed, direction of flow, classification etc. The technology in loop detector and magnetic field sensors uses electro-magnetic voltage effect. They are cost effective and can be easily installed on the road (Timothy *et al*., 2007). But these kinds of sensors do not inherently detect the velocity and direction of the car in a single package. For example, several magnetometers are needed to detect the velocity of a car (Timothy *et al*., 2007). It lacks with the real time property. So, a customized architecture of sensor is needed for the proposed SHS. The prototype sensor consists of two sensing wires and a micro-controller. There is a small distance d between the wire segments. The wire segments are joined with the micro-controller. To sense vehicle the sensing wire can be equipped with electro-magnetic wave or weight pressure. Electro-magnetic wave is more sensitive than weight

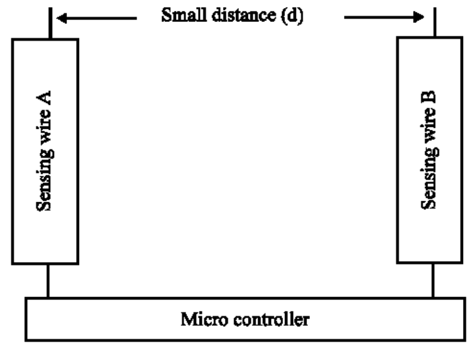

Fig. 1: Architecture of the prototype sensing module

pressure and thus, garbage data can be sensed because of the presence of other environmental issues like heat (Timothy *et al*., 2007). It is also sensitive to light-weight vehicle such as rickshaw, bi-cycle, motor-cycle etc. These vehicles are often travels on the road and do not need to be included in highway safety system. Considering their low speed, the proposed SHS is designed without these vehicles. Although, electro-magnetic wave is cost effective but to make the SHS simple, weight pressure threshing is the best technology for the prototype sensor. The architecture of the prototype sensing module is shown in Fig. 1.

The prototype sensor (Fig. 1) proposed is event driven. The sensors are deployed on the roads and the distance among the motes are specified by the system developer. When, the car passes over the sensor, the sensing wires of the sensor got activated. When there is no vehicle, the sensor does not need to activate the micro controller attached to it. It calculates the velocity by taking the difference of time between the sensing wires and detects direction by checking, which wire is touched first. These two data are saved in the memory of micro-controller and are transmitted as v-message (vehicle message) to the base station.

System data model: The proposed SHS follows the data model of TinyDB (Madden *et al*., 2005). Sensor network builds one big virtual table called SHS sensor table. The table is partitioned over all nodes where one row is constructed per node per instant in time. The columns are the attributes of the network and they include sensor readings, node id and location. Node returns NULL for missing sensor attributes as the data in table are constructed in a time-stamp. The table is created from the event driven operation of the sensors. The readings of a sensor is carried out by others sensors along with its own reading. This appending is done on a single time-stamp. The value of the time-stamp is fixed by the system developer. In this technique, the base table gets the sensor reading and can create a scenario of the whole highway in a particular time-stamp.

Selection of link layer, routing protocol and automatic route initialization: Link Layer and Routing Protocol for the System: For the SHS we choose RMAC (Du *et al*., 2007) as link layer protocol which is more reliable in the context of less data loss than S-MAC and shows better performance in multi-hop environment (Du *et al*., 2007). As the network is fixed, we need a routing protocol that increases the throughput of the system. Madden *et al*. (2005) uses multi-hop tree based routing to implement the TinyDB. The basic reason for selecting multi-hop tree based routing is its efficiency in energy consumption in fixed network (Madden *et al*., 2005). As the proposed SHS is configured with one base station, the base station must be the root of the routing tree. A spanning tree will grow taking base station in the root and covering the whole road sensor. According to Madden *et al*. (2005), the tree based routing creates an epoch level and helps the sensor nodes to act in less time in a communication scenario of data transmission by the sensors.

Route initialization: This protocol uses the reverse modification process of Directed Diffusion (Intanagonwiwat *et al*., 2003). The protocol needs two message formats. One is called r-massage (root message) and other is s-message (reply message) and these messages are formed on the SHS data structure. The r-message contains three attributes. Field 1 is the flag R, field 2 is the root id given by the sensor from its sensor id and field 3 is an epoch value that suggests the number of level the message should travel. The s-message is the response of sensors after receiving r-message. It contains four attributes including the flag S, own sensor id and sensor's positional values. The X, Y values. The system developer must specify the base station with a periodic route initialization time and runs the route initialization from the base station. The algorithm also runs in every node including the road sensors.

In the automatic route initialization (Algorithm 1) when a node receives a r-message it first check if the time is for receiving new r-messages. After receiving a valid r-message the node store the value in the root id as it's root id and replace the field 3 of r-message with epoch = epoch -1 and root id field with it's own sensor id (Algorithm 1, Line 8-13).

Then, it creates a s-message and wait for the s-messages from other nodes to append for twice epoch time (Algorithm 1, Line 14). After a time out it broadcasts the s-message (Algorithm 1, Line 18-20).

Algorithm 1: Automatic route initialization

```
1   While True do
2       Check the buffer for messages;
3       If buffer is empty then
4           Continue;
5       else
6           Rcv (m); {Rcv (m) – receive message with m type flag. R
            and S is the values of m.}
7           If m = R then
8               Store the root id in the data structure if route
                initialization time is over. Otherwise discard the
                message and continue;
9               Create a r-message where Root id = own sensor id and
                specify the time for receiving new r-message further;
10              Epoch⇐epoch-1;
11              If epoch≠0 then
12                  Bcast (R); {Bcast(m)-Broadcast message with m
                    type flag. R and S is the values of m.}
13                  Time-to-live⇐2×epoch;
14                  Create s-message with own sensor id and x,y values
15              end if
16          end if
17          If m = S then
18              If time < time-to-live then
19                  Append s-messages;
20              end if
21          end if
22          If time > time-to-live then
23              Bcast (S);
24          end if
25      End if
26  End while
```

Automatic detection of node failure: The automatic detection of node failure algorithm is inherent in automatic route initialization in Algorithm 1. The process of automatic node failure detection begins by creating the epoch value that is fixed by the system developer for Algorithm 1. This value can be predetermined as safety multi-hop level or can be calculated from base table using epoch ranging. The base station runs the Algorithm 1 for automatic route initialization, collects the s-message from road sensors and compares the collected s-message with base table. If all nodes are present with correct position values, the base station can proceed to carry out its collision detection task. Otherwise, a report is forwarded to the nearest check post for farther action.

Sensor data passing strategy to and from the base station: When a sensor got activated, it sends the v-massage (vehicle information). The v-message encapsulates velocity, moving direction of the car and the sensor id which senses the vehicle. The road sensor appends its rood id with the v-message and broadcasts it. When some sensors capture the v-message, it checks its own id with the root id field of the v-message. If the two id matches, the sensor just changes the root id field of v-message with its own root id and broadcasts it. Otherwise, it simply drops the packet. In this strategy, the sensed vehicle information reaches the base station.

An energy efficient semantic routing tree can be formed to propagate the warning message to the sensor that need to be warned. The semantic routing tree follows the rule of Semantic Routing Tree (SRT) rules of TinyDB (Madden *et al.*, 2005) and thus, ensures energy efficiency by using minimum number of nodes to propagate the signal to the base station. The base station broadcasts the warning message with co-ordinate values (x, y) of the position of the warned sensor id. If any node, stays inside the virtual rectangle formed with the coordinates of base station and the sensor to be warned taken across the diagonal, will broadcast the warning message. But any sensor, outside of this rectangle, does not perform to build the semantic routing tree.

When the base station gets the v-message, it retrieves the sensor id of the message and saves in current record (Algorithm 2, Line 2-6). If the car is heading towards the right direction, the next sensor id is retrieved and a predicated reaching time is calculated for the sensor. This value is stored in forward queue sorted in ascending order (Algorithm 2, Line 8-12). Otherwise, the value is stored in backward queue sorted in ascending order (Algorithm 2, Line 13-18). For accurate time prediction the law of motion is passed through a linear kalman filter (Eq. 1-3):

$$t = \frac{-v+\sqrt{v^2+2\times a\times s}}{a} \quad (1)$$

The linear Kalman filter equations are:

$$x_{k+1} = Ax_k + Bu_k + w_k \quad (2)$$

$$y_k = Cx_k + z_k \quad (3)$$

In Eq. 1 the time t is Measured from initial velocity v, constant acceleration a and the sensor space distance s. In Eq. 2 and 3, A, B, C are matrices, K is the time index, u is a known input to the system, y is the measured output and w, z are noise in process and measurement, respectively.

The algorithm Activation of safety services (Algorithm 3) runs along with the algorithm Enqueue base table (Algorithm 2). The condition for velocity limit violation and detection of unnatural events are stated in line 1-5 of Algorithm 3. The curved and intersection node collision detection are explained between the lines 7-19 of Algorithm 3. The deactivation of the signal is done by the sensor when a vehicle passes over as it is hardwired in the prototype sensor.

Algorithm 2: Enqueue base table

```
1  While True do
2     listen to the incoming channel;
3     If Data available in the buffer of the base station and the message is
      v-message then
4         Report time t1;
5         Extract the message and check the sensor id I;
6         S_i.C_j3(t1, v, d); {S_i.C_j3(t, v, d)-enqueue the time t, velocity v
          and direction d in the j3th position of "current record table of
          base table" for sensor idi.};
7         J3 = j3 + 1;
8         If the direction of the car is in right direction then
9             i = next forward sensor id of I from "base table"
10            compute predicted time t2 for next forward hope I; {use
              equation (1)-(3)}
11            S_i.F_j1(t2); {S_i.F_j1(t)-enqueue the time t in the j1th position
              of the "forward table" of "base table" for the sensor id i.}
12            j1 = j1 + 1;
13        else
14            I = next backward sensor id of I from "base table";
15            Compute predicted time t2 for next backward hope I; {use
              Eq. 1-3}
16            S_i. B_j2(t2); {S_i. B_j2(t)-enqueue the time t in the j2th position
              of the "backward table" of the "base table" for sensor id i.}
17            j2 = j2 + 1;
18        end if
19    end if
20    Traverse the "base table" using activation function.
21 end while
```

Algorithm 3: Activation of safety services

```
Require: called by the algorithm "Enqueue base table"
1         If v is greater than the specified velocity then
2             Report velocity limit violation;
3         end if
4         if "forward table" or "backward table" or both become obsolete
          for a specified time for any two sensor id structure of base sation
          then
5             Report unnatural event;
6         end if
7     If any node contains both the forward and backward values then
8         Warn a signal to the position of the sensor id.
9     end if
10    if two consecutive id contains forward and backward values in a same
      lane then
11        Warn both the ids.
12    end if
13    if any one of the intersection nodes contain values in forward queue
      then
14        Check other intersection nodes of the lanes of intersection;
15        Calculate all entance entl and exit time ext1 of vehicles;
16        if any pair of values ent1 and ext1 overlap then
17            warn the intersection nodes;
18        end if
19    end if
20    remove the entry from "forward table" or "backward table" which
      creates a warning signal. Also remove any obsolete entry respective to
      current time of base station.
21    Return:
```

RESULTS AND DISCUSSION

A simulation of the proposed system was performed using the algorithms and protocols have discussed. All programs are written in programming language C and the simulation model is taken from the data sheet of Tossim on mica motes (Anonymous, 2009a, b). The average latency of hop-counts are figured from the experimental

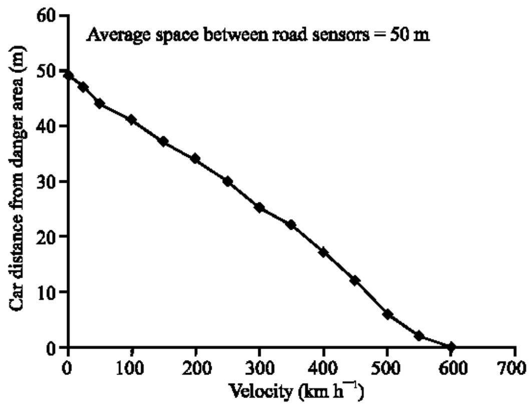

Fig. 2: Car velocity vs. car distance from danger area

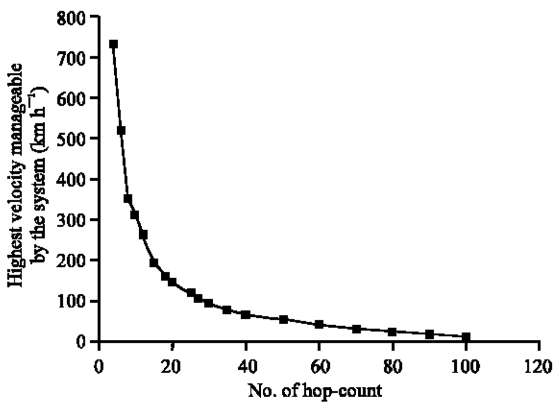

Fig. 3: Number of hop-count vs. highest velocity manageable by the system

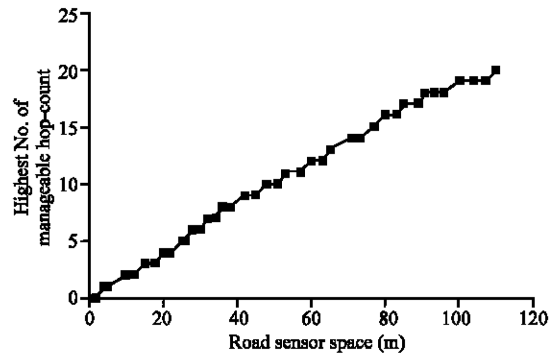

Fig. 4: Road sensor space vs. highest number of hop-count

result of (Sung *et al*., 2007). All data in the test use random distribution of nodes and car velocity. The Fig. 2 shows that, if average spacing of road sensors is 50 m with the highest 5 hop-count, the highest velocity level for the SHS is 550 km h^{-1}. If vehicles travel at 60-150 km h^{-1}, they get warning signal when they are average 30 m away from the danger area. It is acceptable for normal condition where the substantial car velocity is 40-150 km h^{-1}. In the Fig. 3, we try to consider the number of nodes employed in a certain area. The result shows that if large numbers of nodes are deployed in a certain area the system reduces the highest manageable velocity level. For 100-120 km h^{-1} the node deployment must not exceed >35 hops. From Fig. 4, we can specify that if the road sensors spacing is low, the number of hop-counts should be low for the SHS. For fixed number of nodes if the road sensors are placed more apart from each other, the SHS will perform better. If the highest velocity of a car increases, the distance among detector sensors need to be increased to make the system work correctly.

CONCLUSION

This study works to increase highway safety in developing countries like Bangladesh using a cost effective Smart High-way System (SHS). The SHS employs a sensor network to track vehicle velocity, position and moving direction and using these readings it sends warning signals to the possible danger area of the road. The simulation result shows that the drivers will get enough time to react after receiving the warning signals if the system is configured with the highest estimated car speed. When the network is configured with the highest 5 hop-count to the base station and road sensors are placed average 50 m apart, vehicles, driving at 250 km h^{-1} (above substantial value in highways), will cover only 10-15 m before getting warning signal. So, the driver gets enough time to react about the possible danger in advance. Although, human reaction phenomena on receiving warning signal is not considered in the SHS, the proposed system assumes the best possible reaction from the driver to avoid accidents. Unlike other implementation (Timothy *et al*., 2007; Sung *et al*., 2007), the proposed SHS combines different road accident scenarios in a single framework. Apart from reducing accidents, the SHS also reports velocity limit violation and helps to analyze traffic system.

The ease of installing the SHS with minimal human interaction in different geographical condition is preserved by the self-constructing automatic route initialization. The features in the algorithm, like detection of node failure and re-constructing the network, increase the mobility and stability of the system. In this study, the energy modeling of the system is not analyzed. But specifying the event driven operation of proposed prototype sensor and using energy efficient data model of TinyDB, the SHS maintains energy efficiency. The modification of Directed Diffusion in message passing strategies have discussed minimizes network congestion and thus, increases integrity of the sensor readings.

This framework of the SHS can be extended to the complex traffic management system in urban areas, which is currently vulnerable to increasing road traffic. Besides, implementation of WSN can be used as a framework for other warning systems (for example flood monitoring system) in developing countries.

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