Sensor Network based Adaptable System Architecture for Emergency Situations

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***Abstract*—A novel wireless sensor network architecture designed for gathering and managing onsite dynamic information in emergency situations is presented. The system can operate in two different states-normal and emergency, where switching between states occurs according to perception from the environment. The main functionalities of the system include perceiving, processing and sharing the gathered information within a wireless sensor network which is deployed in a multi-story indoor environment. Algorithms for sensor localization, network self-configuration as well as data filtering and prediction are studied in the characterized emergency environment. The proposed architecture will act to reduce risk in rescue operations following an emergency as well as generating early warnings of possible emergencies.**

***Index Terms*—emergency response, localization, self-organization, sensor fusion, wireless sensor networks**

I. Introduction

Emergencies such as fire, gas leakages, earthquakes, tsunamis, terrorist attacks bring long lasting suffering to any society or a country. Disasters such as the New York 9/11 incident, 2004 South Asia tsunami, 2012 earthquake in Japan provide strong evidences for such emergencies. Due to the severe loss of human lives and valuable assets, there is an increasing interest in proposing improvements in the ability to respond to emergencies with the aim of minimizing the severity of the impact caused by an emergency.

Wireless sensor networks (WSNs) raise many exciting opportunities to minimize the impacts caused by emergencies, [1], [2] these studies show the benefits of a sensor network to support Emergency Response (ER).

WSNs have found their way into a wide variety of applications and systems with vastly varying requirements and characteristics. It is currently a very actively investigated research area in communications and computing internationally.

WSNs are an attractive option for indoor environments today, due to the recognition of the importance for energy conservation [3] and emergency/rescue operations [2] - [4]. While sensor networks can be installed in new buildings at the time of construction, they can also be easily installed in older buildings due to their wireless nature. WSNs require that a large number of sensors be positioned easily and that they configure themselves to perform the tasks needed without human intervention.

Unfortunately there is a lack of coherence among research that has been reported for emergency support area. Correct decision making from the corrupted data gathered from the WSN, energy efficiency of sensor nodes [3] routing of data through sensor networks, localization of nodes [5] and self-configuration of sensor nodes in a network [6] are the most important aspects in emergency response, which is not properly addressed in a common WSN architecture.

Proper design architecture for a wireless sensor network is crucial in the development of systems for complex and dynamic environments such as emergency response, especially when the WSN is deployed in a multi-story building. Therefore, in such a domain, architecture based on an accurate design could prevent many disasters.

In this paper, our main focus is to illustrate the novel sensor network based adaptive system architecture for emergency situations. The system is highly adaptable in both non-emergencies to emergency situations and vice versa.

A brief review of related works is provided in Section II. The challenges in an emergency response environment are presented in Section III. The proposed WSN architecture is presented in Section IV. Since our main contribution is at the core layer, each sub layer in the core layer is described in Section IV, V, and VI. Conclusion and future work appear in Section VII.

II. Related Work

Currently a lack of coherence is observed among research that has been reported for WSN architecture related work in the domain of emergency; directly addressing the research aspects of sensor fusion, energy consumption, self-organizing, localizing etc. Thus, the findings of this study become significant and unique. The work reported in [2] proposes a high-level conceptual architecture of the system that is capable of deploying the human computer interfaces suitable of supporting various fire fighter job roles during a fire ER. This research addresses only fire emergency situations, and also it is mainly concerned with data capturing, decision making and presentation. Localizing and optimizing the network parameters are not captured in the above research. The majority of the previous work [1] - [7] that has been reported propose emergency architectures that do not

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capture all the above research aspects (i.e. Self-organizing) and the relationship among those, also the adaptability in the two modes (emergency and non-emergency) is not addressed.

III. Challenges in Emergency Response Environment

The nature of an emergency is highly dynamic and demanding. Real-time data retrieval, processing and management are required.

Sensor node failures, communication link failures and noise added to the multi-modality sensed data are common challenges in WSNs which introduce uncertainties in the overall system. Communication time delays directly impact on real-time data retrieval and also introduce errors in the estimation of dynamically varying environment.

During an emergency, first responders may add stationary and mobile sensor nodes to the WSN. Integrating and tracking the newly added nodes is also a challenge.

Basically during an emergency following major challenge can be highlighted.

- Highly dynamic and demanding environments
- Real-time data retrieval, processing and management
- WSN may lose its existing sensor nodes or add new sensor nodes to its network during an emergency
- Communication link failures
- Noise added to the multi-modality sensed data
- Communication time delays

IV. Proposed Architecture

This paper presents a novel architecture which can cope with emergency situations such as fires in a multi-story indoor environment using s WSN. The system will function in two main states – normal and emergency, where the former describes the functionality of the system under non-emergency situations and the later describes the functionality of the system under emergency conditions where several adjustments are needed to be done.

The proposed layered architecture shown in Fig. 1 consists of three major layers namely, the communication layer, the core layer, the presentation layer which will collaboratively function to create a complete WSN which can be adaptable for emergency situations. Each layer consists of sub layers as described below.

A. Communication Layer

1) Physical and medium access controller layers

These layers are responsible for the physical arrangements of sensor nodes and communication among them including medium access. Sensor nodes' deployment topology, power levels, frame rates and antenna arrangements are few major things to be considered.

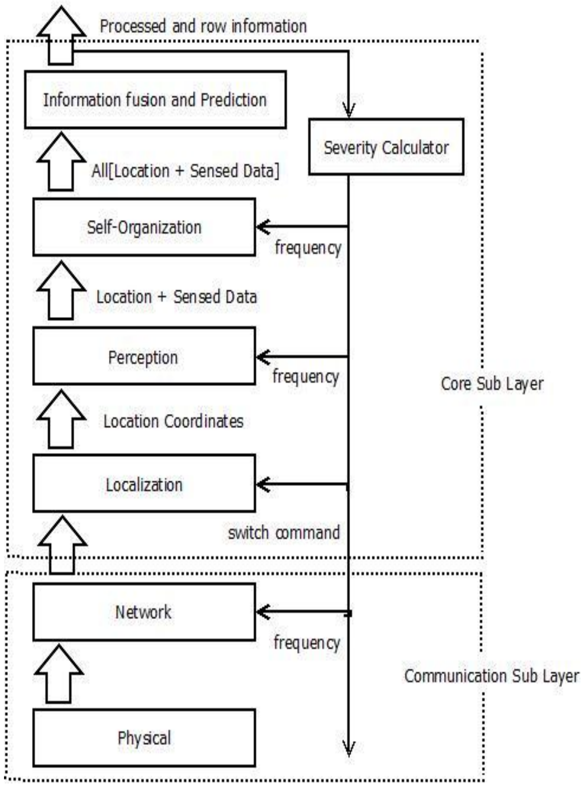

Figure 1. Proposed architecture

B. Core Layer

The output of the communication layer feeds as the input to the core layer and passes relevant fused and predicted messages to the presentation layer. Core layer consists of five sub layers, the localization layer, the perception layer, the self-organization layer, the data filtering and prediction layer and the severity calculator layer.

1) Localization

This is the layer where the sensor nodes will be located with either absolute or relative coordinates. Since the environment is indoor and dynamic it is more suitable to use a distributed localization algorithm with range-free techniques. Then the location information will be passed to the upper layer to combine with environment sensed data as shown in Fig. 2. The detailed description of this layer is in Section V.

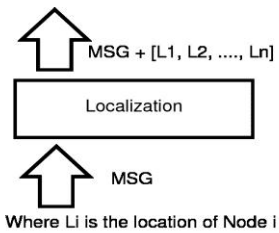

Figure 2. Function of localization layer

2) Perception

This layer will collect all the data generated at the sensor nodes. The data will be a collection of information such as temperature, humidity, air quality, smoke and so on of the monitoring environment. This perceived date will then be combined with location information and passed on to the upper layer for further processing. Fig. 3 shows an overview of the layer.

3) Self-organization

This is the layer where clusters are created dynamically. All the sensor nodes within the cluster will communicate with their local cluster head first and only the cluster heads will communicate with the upper layer thereafter. This process will efficiently contribute to save the energy or power of the whole WSN. Perceived data combined with location will then be passed to the upper layer for further processing. Fig. 4 shows an overview of the layer. The detailed description of this layer is in Section VI.

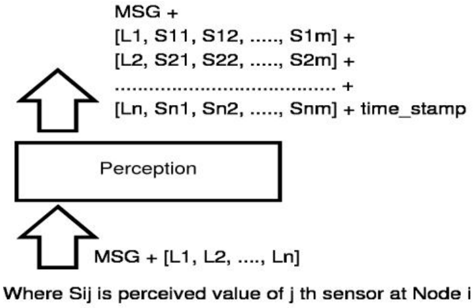

Figure 3. Function of perceiving layer

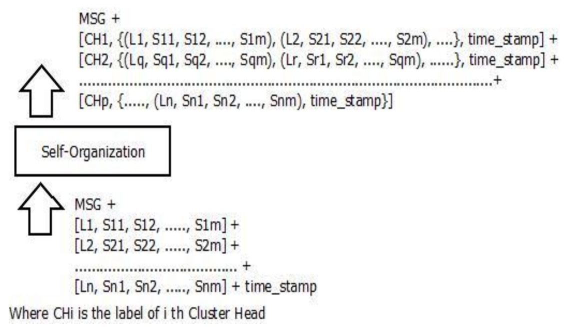

Figure 4. Function of self-organization layer

4) Data filtering and prediction

This is the layer where the data manipulation and calculations take place. It uses the received data from the lower layer as inputs and provides predictions on dynamically varying situations using knowledge based algorithms. Depending on the output of this layer several actions will be taken. The processed data will then be passed to both the presentation layer and the severity calculator. Fig. 5 shows an overview of the layer. The detailed description of this layer is in Section VII.

5) Severity calculator

Provides feedbacks to the sub layers in order to adapt the system. In this layer most of the important parameters such as network refreshing rate, perceiving rate, clustering rate will be set. On the other hand it will switch the node localization algorithms if there is an emergency. Fig. 6 shows an overview of the layer.

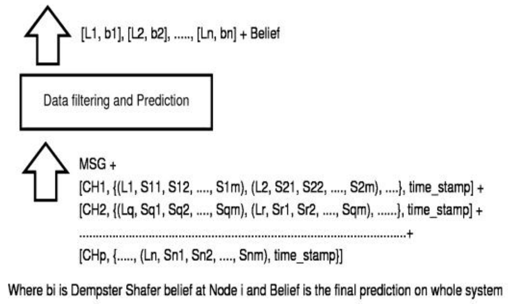

Figure 5. Function of data filtering and prediction layer

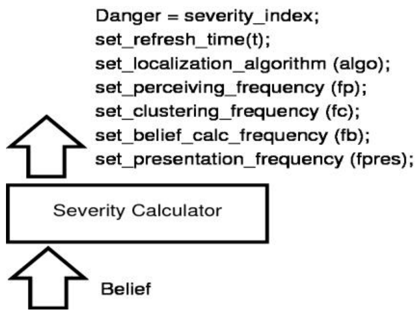

Figure 6. Function of severity calculator layer

After calculating the severity index of the environment, the whole system will get reconfigured if there exists an emergency. For an example if there is a medium strength fire, then the system will adapt to that by changing its refreshing rates, moving to a different localization algorithm and perceiving the environment more frequently until the environment become normal. This process will repeatedly run throughout the system.

C. Presentation Layer

1) Presentation

This layer is responsible for taking the necessary actions according to the output of the data filtering and prediction layer. Conditions of the environment could be presented as an easily readable map. On the other hand this layer could be used to inform the conditions of the environment to relevant parties (i. e. first responders) if an emergency has taken place.

V. LOCALIZATION

A. Introduction

Most of the sensor nodes in a WSN do not know their own location due to unavoidable constraints on the cost and size of sensors, energy consumption, the implementation environment (e.g., GPS is not accessible in some environments; indoor) and the deployment of sensors (e.g., sensors may be randomly scattered in the region). WSN localization techniques are used to estimate the locations of these location unknown nodes. The nodes with known locations are called ‘Anchors’. Locations of anchors can be obtained by using a Global Positioning System (GPS) or by installing anchors at points with known coordinates. Therefore sensor nodes with unknown locations need to be estimated their locations relative to anchors using a localization algorithm.

On the basis of mechanisms used to estimate the locations, WSN localization algorithms can be divided broadly into two categories; ranged-based and range-free. Range based techniques exploits the either distance or angle information between neighbor nodes and then uses the trilateral or multilateral localization methods to locate the unknown nodes, such as TOA, AOA, TDOA and RSSI [8]. Range-free algorithms use estimated distances between nodes instead of measured distances locate the sensor nodes. Several such range-free localization algorithms are Centroid, DV-Hop, Amorphous, MDS-MAP and APIT [9] Range-based approaches need more sophisticated ranging hardware to measure point to point distance or angles between nodes. Even though range-based localization can produce more accurate localization results, they are more expensive compared with range-free localization techniques. Therefore range-free algorithms attract more attention to overcome the high cost of hardware facilities and energy consumption required by range-based approaches.

B. *Objective and Aims of the Layer*

Even though localization is one of the main aspects in WSNs, it has so many challenges to overcome. Few of them are node failures, signal interferences, packet losses during transmission, power efficiency and cost effectiveness. On the other hand most of the existing localization algorithms have used some unrealistic assumptions such as nodes are uniformly distributed, nodes are static, and network topology will not be changed and no communication failures among them. However in an emergency situation those assumptions are no longer valid and most of the existing algorithms including below describes DV-Hop algorithm become to fail. Therefore the main objective of this layer should be locating the sensor nodes with the minimum localization error under both normal and emergency situations.

C. *Previous Work on Localization*

The DV-Hop localization algorithm proposed in [10] is an attractive option for localization in WSNs. It is a distributed algorithm with low processing requirements. The basic idea behind the whole algorithm is the distance between the unknown nodes and anchor nodes are expressed by the product of average hop distance and the hop count. The algorithm consists of three main steps.

1) *First step*

Each anchor node broadcasts a packet throughout the network containing anchor's location and the hop count initialized to one. Anchors with higher hop count values to a particular anchor will be discarded so that each anchor node maintains a minimum hop count value to each other. Then all the anchor nodes pass the packet while increasing the hop count value in each hop between nodes and ultimately all the nodes in the network get the minimum hop count to every anchor node.

2) *Second step*

After anchor nodes receive the minimum hop count values to each and every other anchor nodes, they will calculate the average hop size of one hop using the following formula.

Estimated average hop distance for anchor node *i*.

$$Hopesize_i = \frac{\sum_{j\neq i}\sqrt{\left(x_i - x_j\right)^2 - \left(y_i - x_j\right)^2}}{\sum_{j\neq i} hops_{ij}} \tag{1}$$

where (x_i, y_i) and (x_j, y_j) are coordinates of anchor nodes *i* and *j* respectively and hop_{ij} is the hop count between the anchor nodes *i* and *j*.

Each anchor node broadcasts its hop size to the network. Each unknown node saves the first hop size value it receives through the network while passing the same to the neighboring nodes so that most of the unknown nodes gets the hop size value of the anchor nodes that has the least hops between them.

$$dist_{ij} = \left(Hopsize\right)\left(hops_{ij}\right) \tag{2}$$

3) *Third step*

When an unknown node receives three or more distances from anchor nodes it will use trilateration, multilateration or maximum likelihood method to estimate its location.

D. *Proposed Approach for an Emergency Response*

Various improved localization algorithms have been proposed by many researchers to gain a better localization error [5], [11], [12]. However, most of them cannot be used in emergency situations due to their unrealistic assumptions.

The localization algorithm suited for an emergency environment need to be addressed the issues of anchor nodes failures, introducing mobile nodes, randomly adding new nodes with unknown locations, network topology changes and communication failure occur between sensor nodes. The bottom line is that the localization algorithm should be more realistic in localizing the sensor nodes in an emergency situation.

VI. Self - Organization

A. *Introduction*

The ad-hoc deployment of the sensor nodes, prevent pre-planning of the network organization. Hence these networks need to self-organize themselves to interact with their environment to monitor or sense physical parameters and transmit this data to a central location.

B. *Objectives and Aims of the Layer*

This layer is concerned with organizing the ad-hoc deployed sensor nodes to collect the sensed data and transmit those to the application layers to make decisions. IEEE 802.15.4 standard is the most popular standard used in Wireless Sensor Networks, due to its characteristics. In this standard, Carrier Sense Multiple Access (CSMA) transmission method is used as the Medium Access Control (MAC) layer communication protocol. This transmission protocol need to be incorporated with a self - organization algorithm to optimize the drawbacks of

CSMA such as an unnecessary drain of energy which can result due to over hearing on broadcast communication, overhead of control and redundant data packets.

Hence the main aim of this layer is configuring nodes by themselves to communicate with their neighbors by optimizing the network parameters such as energy consumption of the nodes, communication delay, re-transmission of packets and etc. In a wireless sensor network one of the most critical parameters is considered as energy usage, i.e. because in a sensor node one of the scarce resources is energy. The node uses batteries that are intended to last for a long period of time by careful duty cycling [1].

Self-organization layer receives the location of each sensor node from the location layer and these locations can be used in time self-organizing algorithms. This is an advantage of the proposed architecture. It can reduce complexity of the computation as well as the energy needed for those calculations. Then the collected data in this layer are passed onto the data filtering and prediction layer with the location of each node for the initial processing.

C. Previous Work on Self-organization Algorithm

The WSN based indoor emergency applications require periodic data collection from the distributed sensors to one central location. The energy usage of such a network can be reduced by compressing data and decreasing wasteful energy consumption as a result of overhearing and retransmissions due to packet loss. The clustering algorithms have been identified as an effective energy saving WSN self-organization method under which above techniques can adopt. In clustering algorithms there are few aspects need to consider such as how to select a Cluster Head (CH), CH density, how clusters are formed and when re-organization occurs.

Some algorithms choose CH randomly (e.g. LEACH (Heinzelman *et al*. [13]), SEP (Smaragdakis *et al*. [14])) and some based on the residual energy of the node (e.g. HEED (Younis & Fahmy [15]), EDCR (Gamwarige S. *et al*. [3])). Some drawback of selecting CHs randomly is node with very low battery power can become a CH which results in that dying node very quickly. LEACH and SEP algorithms predefined a value to CH density but in HEED and EDCR it considers the communication range of CH and find a value for density separately for each network. Especially in EDCR, it has optimized the communication range of the node based on energy. One drawback in predefining CH density is no control over the CH distribution in the network which will lead to unnecessary energy consumption. In cluster formation, LEACH, SEP, HEED algorithms consider the distance from CH to particular node but EDCR considers both distance and residual energy of the CH. Hence the EDCR algorithm has been able to prolong the lifetime of the network. Then the most important and challenging aspect is how re-organization occurs. LEACH, SEP, HEED algorithms re-organize the network after a certain number of data rounds and EDCR does that when the CH residual energy drops below a threshold value. By that also EDCR algorithm has been able to prolong the lifetime of the network. But none of the algorithms do not consider re-organization of the network in an emergency situation. Therefore in such a situation network recovery time is much higher which a major drawback. And also due to the re-organization method used in EDCR, it takes long time to recover the network in an emergency compared to other three algorithms.

D. Proposed Approach for an Emergency Response

Many researchers have proposed many self-configuration algorithms to optimized network parameters. Among those most researches try to optimize the lifetime of the network none of them try to propose a self-configuration algorithm suitable for an emergency situation. In such a situation wireless sensor network need to re-organized their nodes according to the requirement. The critical data in the network i.e. data carrying about emergency situations, need to give high priority in transmission, and the sensing frequency and data gathering speed need to increase. In this adaptable architecture if an emergency situation detected from data filtering and prediction layer, those alerts sent to the other lower layers. Hence from those data, re-organize the network to reduce the network failures such as communication drop of the network, critical node failures etc.

Another important aspect which has not been considered in one of the algorithms is how this clustering method can be applied to an indoor environment to perform better data fusion in CH. For an example if clusters form between two rooms in the building, CH in that cluster cannot make a better decision regarding any of the rooms. Therefore it is a best method to form clusters with the nodes located in one room or common area.

VII. Data Filtering and Prediction

A. Introduction

A wireless sensor network deployed in a multi-story building for collection of parameters related to emergency situations, energy consumption, building environment, human behavior inside the building etc. needs application layer protocols to filter the corrupted data and infer on the event of interest

B. Objectives and Aims of the Layer

Data filtering and prediction techniques are needed for an application to ensure reliability and accuracy of information obtained from the WSN. Maintaining a knowledge base within the network with sophisticated machine learning techniques will reduce the risk at emergency. However, running high end algorithms will also impact on the power in sensor nodes, central nodes. Therefore the accuracy and the power should be compromise effectively.

In this layer we are concentrating on proposing an approach to develop a common knowledge based framework to predict emergencies for generating early warnings, effectively predict the emergency propagation (speed and direction of the emergency estimation) in the building.

The particular knowledge based approach propose here basically achieved two tasks;

The first task is to detect an emergency and give early warnings to the presentation layer and the lower layers (reporting the possible emergency emerging locations and the severity of the incident. Based on the severity of the warning;the presentation layer should decide whom to inform and the way to inform the emergency).

The second task of this layer is to predict on the propagation of the emergency incident by estimating the speed, direction of the incident. Possibly building propagation maps (belief/plausibility or probability maps) will reveal certain important characteristics of an emergency.

C. Previous Work on Sensor Fusion

Emergency situations are highly dynamic where the state of the environment changes very frequently. Predicting on dynamic states is one of the most challenging tasks in this layer. Bayesian filtering, Kalman filtering, Fuzzy theory, Neural networks, Dempster-Shafer (DS) formalism are being used as sensor fusion, information fusion techniques.

The advantages in Dempster-Shafer theoretic methods become evident when the assumptions typical of a Bayesian approach (e.g., conditional independence, availability of prior knowledge, joint probability distribution etc.) are difficult to justify [16]. The knowledge based framework developed in this layer is mainly built based on Dempster-Shafer theory due to the above mentioned advantages.

Evidence Filtering [17], [18] is an effective approach developed to deal with dynamic environments, by integrating Dempster-Shafer theory with discrete time filtering techniques.

Adding several dimensions to the existing evidence combination methods [19], [20] via ordering the incoming evidences temporally and spatially would reveal certain information hidden in the evidences. While modeling information coming through different types of sensor modalities and making direct inferences on both frequency and time domains is possible with the Evidence Filtering.

Temporal Evidence Filtering and Spatio temporal Evidence Filtering approaches are given in [17] - [21]. In both cases the sum and positive conditions on the filter coefficients should be satisfied to ensure that the output evidence signal constitutes a valid DS belief function.

D. Proposed Approach or an Emergency Response

In a multi-modality sensor network employing large numbers of inexpensive sensors, during an emergency several factors can contribute to data imperfections including inaccuracies, uncertainties and ambiguities in the information gathered.

The evidence filtering technique is capable of handling these data imperfections in a robust manner using DS theoretic beliefs. DS approach is chosen due to the advantages of its behavior in sensor network characteristics (i.e. no prior information is needed).

However, the linear time invariant evidence filter is converted to a time varying non-linear filter due to the dynamic behavior of the emergency situation. In this paper we have limited our scope to time varying linear evidence filter.

1) Proposed Demspter-Shafer frame of discernment (FOD) for emergency response:

FOD= {no emergency, low_1, low_2…, low_n, $medium_1$, $medium_2$, mediumm, high}

There are 2^{n+m+2} numbers of hypothesis, including null hypothesis which is equal to 0 according to the DS theory. Here the low_n, $medium_m$ and high indicate the severity levels of the emergency.

2) High level steps in the linear time varying Evidence Filter algorithm to detect/predict emergencies:

i. Dempster-Shafer belief functions can be calculated for any hypothesis for all the modalities separately.
ii. Fuse evidences from all the modalities, using the belief functions calculated in step 1.
iii. Evidence signal should be modeled according to the fused belief/plausibility value by incorporating time and space.
iv. Input evidence signal should be passed through the time varying evidence filter. Evidence filter equation may take the difference equation format (3) or state space model formulas.

$$\beta_{p,q,r} \geq 0, Bel(B)(x,y,t) \sum_i \sum_j \sum_k \alpha_{i,j,k,} Bel(B)(x-i, y-j, t-k) + \sum_p \sum_q \sum_r \beta_{p,q,r} Bel(B \setminus A)(x-p, y-q, t-r) \quad (3)$$

$$\alpha_{i,j,k,} \beta_{p,q,r} \geq 0, \sum_i \sum_j \sum_k \alpha_{i,j,k} + \sum_i \sum_j \sum_k \beta_{p,q,r} = 1 \quad (4)$$

Here the first term captures the best knowledge base and the second term capture the portion of incoming evidence which is conditioned to the event A. In a distributed, multiple modality sensing environment, it is possible to have different conditioning events depending on the expertise of each node (characterized by the fusion FODs, if A is not known it is assumed to be the FOD).

Here α, β are the filter coefficients, conditions in (4) of filter coefficients should be satisfied to ensure that the output evidence signal constitutes a valid DS belief function. *x* and *y* parameters are space coordinates while *t* denotes the time.

Filter coefficients α, β values are time varying and should be altered according to the perception of the environment. Node failures, communication link failures, characteristics of the building structure, purpose of the filter (i.e. early warning, prediction of emergency propagation) should be considered in order to determine the correct coefficient values.

VIII. Conclusion and Future Work

The work presents in this paper develop an adaptable WSN architecture for emergency situations which is capable of switching between emergency and non-emergency modes. Essentially, the architecture we propose offers a way of minimizing the severity of the impact caused by the emergency using WSNs. The most crucial research aspects localization, self-organizing, energy consumption, multi-modality sensor fusion etc. are incorporated in an effective manner. To our knowledge, no architecture is able to address above research aspects in an emergency with the capability of switching between two states.

However, Each sub layer in the core layer should be further refined to make the behavior of the whole WSN architecture robust in emergency response.

Another important research aspect in WSN is security implications which have not been addressed in this paper. Additionally, it needs to be further explored on other aspects like, providing users the information on highest possible time lines and if a transmission failure occurred, notify it to the user/application as quickly as possible. Further a common data structure needs to be used with higher flexibility and proprietary formats. Futhermore, this architecture mainly focuses on building monitoring systems for emergency response. How can this architecture incorporate with green building applications, need to be investigated.

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