Modeling and Analysis of Wireless Sensor Networks Using Fuzzy Set Theory

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Abstract

For any Wireless Sensor Network (WSN) application, choosing a sensor node depends on two primary criteria. One is sensing coverage that determines how efficiently sensor nodes can detect any event occurring within the target field. The other one is communication coverage that determines how efficiently sensor nodes can send data, gathered by every active sensor nodes, to the central sink node. There is a vagueness present both in sensing and communication behavior of any sensor node. The human like reasoning that best suits for this vagueness is the fuzzy reasoning. To exploit this vagueness, this thesis proposes fuzzy models for sensing and communication behavior with suitable inference rules and appropriate definition of membership functions for the identified fuzzy input and output variables.

Due to the limited availability of energy in every sensor node, its optimized use is one of the main focus in WSN research. Energy can be conserved using various techniques such as grouping sensors into different clusters and periodically send a large number of cluster members into standby mode, rotating connected dominating sets found from sensor nodes, fusing and compressing sensed data at various levels, scheduling nodes with duty cycle technique etc. Efficient fuzzy algorithms can be developed for these cases to conserve precious energy with the successful application of above mentioned two fuzzy models. An unequal sized clustering algorithm is proposed in this thesis applying the above mentioned fuzzy communication model. Simulation results are compared with prior works to show the effectiveness of the proposed technique.

In most sensor network applications, the information gathered by sensors will be meaningless without the location information of the sensor nodes. One of the major challenges in WSN is to determine the location of unknown nodes based on the known location of other nodes. It is highly desirable for a node in wireless sensor networks (WSNs) to self-localize accurately. This thesis also studied the problem and proposed a localization algorithm based on the proposed fuzzy communication model. Results are compared with existing works proves the efficiency of the proposed work.

Target tracking based applications are widely referred as the most interesting applications of WSNs. WSN is used to track the objects in a monitored area and to report their location and other information about objects to base station. It has many real-life applications such as wild life monitoring, security applications for buildings and international border monitoring. This thesis proposed a convoy tree based object tracking algorithm using the proposed fuzzy sensing model. Experiments are conducted with the TelosB mote based network and a significant improvement over the existing research works observed.

All the models and algorithms proposed in this thesis successfully apply the fuzzy theory to preserve the most precious battery energy to enhance the life time of the network. Apart from improving energy situation the algorithms also address some other challenges for different applications such as clustering, localization, target tracking etc., and certainly advances the research on wireless sensor network in a significant step.
1 Introduction

Last decade witnessed a rapid development in micro-electro-mechanical systems (MEMS). Advancement in integrated circuit technology made it possible to develop low cost tiny devices with a rich feature set with very little energy demand. This opens up the development of embedded systems. An embedded device, equipped with different types of tiny smart sensors and a transceiver module is capable of monitoring different desired physical events occurring in its vicinity and are capable of sending the collected data to a central device (called a base station or sink node) which can process it and take necessary actions. These embedded devices are called wireless sensor nodes (see Figure 1).

A network can be formed by a collection of these devices which can collaboratively monitor a specific area of deployment. Such a network is called a Wireless Sensor Network (WSN) (as shown in Figure 2) which provides unprecedented opportunities for a variety of civilian and military applications, for example, environmental monitoring, battlefield surveillance, and industrial process control. In near future, WSNs will be widely used in various civilian and military fields, and revolutionize the way we live, work, and interact with the physical world. WSNs have some unique constraints, such as dense node deployment, the unreliability of sensor nodes, severe energy, very low computation resource, and little storage. These present many new challenges in the development and application of WSNs.

Two most important aspects of WSN applications are i) gathering data efficiently from the application area by deploying a large number of sensor devices, called sensing coverage problem and ii) efficiently transfer the accumulated data from the sensor devices to the sink node called, communication coverage or linking coverage or connectivity problem. Analysis [51, 60] shows that the communication module of sensor node is the most energy consuming units. So turning off that module by judiciously selecting the sensor nodes, it is possible to conserve a significant amount energy. Sensor nodes use low power and short range communication technique to reduce energy consumption. Hence, the obvious choice is hop-by-hop routing mechanism, where each connected sensor node forwards data coming from the source sensor node to the base station. Initially, a large number of sensor nodes are deployed in the field in a particular pattern to optimize sensing coverage.
Architecture of Wireless Sensor Node: The main components of a sensor node are a processor, transceiver, external memory, power source and one or more sensors as shown in Figure 3. Rectangular blocks drawn with solid lines are the essential components, whereas the blocks drawn with dotted lines are optional components. Processor performs tasks, processes data and controls the functionality of other components in the sensor node. The most common processor is a micro-controller. On-chip memory of a micro-controller and Flash memory are used mostly due to their cost and storage capacity. There are two categories of memory i) user memory used for storing application related or personal data, and ii) program memory used for programming the device. Transceiver uses radio frequency-based communication is the most relevant that fits most of the WSN applications. Transceivers often operate in a few states such as transmit, receive, idle and sleep. Most transceivers operating in idle mode have a power consumption almost equal to the power consumed in receiving mode. Thus, it is better to completely shut down the transceiver rather than leave it in the idle mode when it is not transmitting or receiving. Most commonly used power unit is either batteries or capacitors. Batteries, both rechargeable and non-rechargeable, are the main source of power supply for sensor nodes. Sensors measure physical data of the parameter to be monitored and have specific characteristics such as accuracy, sensitivity, etc.
Most sensors are the analog type whose output is then passed through an analog-to-digital converter (ADC) to use with the processor. Example of sensors are: sonar or radar sensor, camera, temperature or humidity sensor and so on. Depending on the application a sensor node may use some optional components. These are i) location finding system which may either use a GPS device or may run some specialized algorithm, ii) mobility system which enables the sensor nodes to move from one location to another, iii) power generation system where sensor nodes try to use some energy harvesting scheme such as from solar sources, temperature differences, or vibration etc.

Applications of WSN: Development of small sensor nodes started back to the 1998 to Smartdust project [39], NASA Sensor Webs Project [11] and CENS [4]. A wide range of applications are possible. These can be categorized as: i) Military applications of sensor network includes monitoring friendly forces and equipment, battlefield surveillance, targeting etc, such as Smart Dust [39], Boomerang sniper detection system [45], DustNet [22] and VigilNet [19]. ii) Some environmental applications of WSNs include tracking the movements of birds, small animals, and insects, monitoring environmental conditions, precision agriculture, forest fire detection, flood detection etc, [5, 16, 20, 23–26, 32, 46, 49, 58]. Some example projects of environmental applications are: the Great Duck Island project [32, 49], the Columbia River Ecosystem (CORIE) [16], the ZebraNet [25, 58], Volcano Monitoring in Volcán Tangaráhu in central Ecuador, Early Flood Detection developed at MIT and tested in Honduras. iii) Some of the health care applications for sensor networks are the provision of interfaces for the disabled, integrated patient monitoring, diagnostics, and tracking and monitoring doctors and patients inside a hospital [17, 33, 36, 40, 41, 54, 55]. Few examples of this type of applications are the Artificial Retina (AR) [40], the CodeBlue project at Harvard University [33] and ALARM-NET [55]. iv) One emerging application of WSN in health is body area network (BAN) [6, 34, 43, 52], also referred to as a wireless body area network (WBAN) or a body sensor network (BSN). This is a wireless network of the wearable or implanted computing devices. These devices may be placed in the human body or surface mounted on the human body in a particular position. The wearable or implanted sensor devices continuously measure different medical parameters of a patient and transmit this data to a nearby handheld device such as a mobile or plum top. The health condition of a patient thus made available to medical practitioner through infrastructure network. v) In home smart sensor nodes and actuators can be attached to appliances such as vacuum cleaners, microwave ovens, refrigerators, and DVD players [38], as well as water monitoring systems such as the Non-intrusive Autonomous Water Monitoring System (NAWMS) [28]. vi) Industrial: applications of WSN are monitoring material fatigue, monitoring product quality, environmental control of office buildings, factory instrumentation, vehicle tracking [7–9, 12, 15, 41, 44, 47, 48, 50, 54]. Some examples are Intel’s semiconductor fabs namely FabApp, structural health monitoring (SHM) [8] and netSHM [7].

The rest of the synopsis is organized as follows. Section 2 elaborates numerous challenges exists which any WSN application developer has to solve. Section 3 presents the motivation behind the development of algorithms for the selected problems of WSN. Section 4 discusses the contribution of the thesis toward the community. Section 5 describes the organization of different chapters in the thesis. And Section 6 finally draws the conclusion.
2 Challenges of WSN Application

Design of WSNs requires ample knowledge of a wide variety of research fields, including wireless communication, networking, embedded systems, digital signal processing, and software engineering. Consequently, several factors exist that significantly influence the design of WSNs. Among the numerous challenges few challenges are discussed here which become the major driving factors for this thesis, such as:

- **Power consumption:** A wireless sensor node is powered by batteries. For most of the applications, it is almost impossible to replenish the power sources. The lifetime of WSN, thus, strongly depends on battery lifetime. Therefore, the most challenging factor of any WSN application is to conserve battery energy as far as possible. Thus, the sources that consume energy during the operation of each node should be analyzed and maintained efficiently. A breakdown of the power consumption of a MicaZ sensor node is shown in Figure 4. It can be seen that a sensor node expends maximum energy for data communication.

- **Sensing Coverage:** Another important aspect of WSN application is the sensing coverage (or in short coverage). Sensor devices used in sensor node have a limited sensing range beyond which it does not sense the physical event. The ratio of the effective monitored area and area of the monitoring region is called the sensing coverage (or simply coverage). Most challenging factor is to determine the deployment pattern which will maximize the coverage.

- **Connectivity:** Communication coverage (or in short connectivity) is another important aspect of WSN application. Since the low power short range radio communication technique is used it is not possible for each node to directly transfer data to the base station. Thus each sensor node must be placed in such a way that they will ultimately remain connected with the base station all the time by a multi-hop network maintaining an acceptable connectivity level.

- **Clustering:** A WSN application uses low power short range communication technique and multi-hop delivery scheme. To accomplish this, a backbone network must be formed to maintain proper connectivity. Clustering technique can be used in this regard. The main challenge of developing a clustering algorithm is to minimize the energy usage. Cluster heads near to the base station have to carry more traffic than other cluster heads. Thus, these cluster heads die faster than others. This gives rise to the so-called hot spot problem. Hence, clustering algorithm designer has to deal with two main challenges such as:

![Figure 4: Power consumed by sensor node at different state](image)
as i) optimizing energy use and ii) solving hot spot problem.

**Localization:** Almost all the applications of WSN need to know from which location within the network information is coming. Therefore, every sensor node must know its location within the deployment area. So, the challenge is to determine acceptably accurate location information in an energy efficient way with very few extra hardware support.

**Target Tracking:** Object tracking is another very important applications of WSN. The main challenges are i) to continuously track the object, ii) send acceptably accurate information about the object to the base station and iii) make the algorithm energy efficient. Tracking multiple targets present in the field is another challenge to the algorithm designer.

### 3 Motivation of the Thesis

Since the wireless sensor nodes are typically battery operated, energy preservation is the most challenging factor. Almost all research efforts, from the very beginning, are trying to optimize the usage of energy. This is the first and foremost motivation factor behind all research efforts on WSN. Development of the algorithms discussed in this thesis is also motivated by the same factor.

In due course, researchers have developed several models [3, 10, 18, 27, 29, 31, 35] to represent different aspects of WSN. Most of the analytical models are not very accurate, also, to improve the accuracy some models become complicated. Analysis of the behavior of the sensor nodes reveals an inherent fuzziness in all aspects of WSN behavior. This fuzziness can be used to model the behavior of the sensor nodes, as well as, to propose algorithms for different aspects of the wireless sensor network to improve the current situation. This remains the main inspiration to propose fuzzy based models and algorithms to solve different problems and improve the performance of wireless sensor network.

The sensing capability of wireless sensor nodes has an inherent randomness. This randomness can be modeled based on fuzzy theory, which can qualitatively relate the effective distance of the sensor nodes from the target object depending on the effective signal strength received by the sensor device at the sensor nodes. Thus the sensing capability of the sensor nodes can be modeled (few existing models are [14, 21, 30, 42, 53]) using a fuzzy inference system. This motivates to propose a fuzzy based model for sensing capability of individual sensor nodes.

Another very important aspect of wireless sensor network is the communication capability of sensor nodes. Most of the sensor network uses radio waves to move the collected data to the base station. The existing models [2, 37, 57, 59] are either very complicated or with restricted features. Analysis shows that there is also a complete fuzziness in the communication behavior of sensor nodes. Therefore, a fuzzy inference system can be developed to model the communication behavior, which takes the received signal strength as its input and gives the effective distance between transmitter and receiver as output. This inspires to propose another fuzzy based model to encompass the communication behavior of sensor nodes.
Clustering techniques are used to deliver collected data to the base station. To reduce the energy demand, cluster members remain in sleep mode most of the time. Whereas, cluster heads remain in active mode all the time in a round to ensure the availability of routing path to deliver data to the base station. So, cluster heads quickly get depleted this energy if those are chosen frequently. To reduce energy demand, the cluster heads are rotated between rounds. All existing algorithms select cluster heads mainly depending on the remaining battery energy. Also, clustering has a hot spot problem. Here also fuzzy technique can be used to improve the situation further. This motivates to propose a new fuzzy based unequal clustering algorithm.

As discussed in Section 2 localization is one of the most important problems in WSN research. Most existing algorithms either use some expensive devices to measure any special parameters (such as Angle Of Arrival (AOA), Time Of Arrival (TOA, or Time Difference Of Arrival (TDOA)) or are not very accurate. Also, another factor is to improve the energy situation further. Again, the fuzzy theory can be applied appropriately in this case. These remain the motivation behind the development of a range free localization algorithm.

One very important application area of wireless sensor network is continuous tracking of moving objects (called target) in its vicinity. One approach to this problem is to build a tree of sensor nodes around the target and dynamically reconfigure the tree depending on the movement of it. Very few existing algorithms guarantee 100% tree coverage, also there is ample scope to improve the energy situation as well as to improve the accuracy of gathered information about the target object. Again, the uncertainty in sensing behavior has motivated to use fuzzy logic to advantage to improve the performance of the algorithm. These inspire to develop another fuzzy based target tracking algorithm.

4 Contribution of the Thesis

This work proposes a sensing and communication model based on fuzzy theory. The proposed fuzzy sensing model (discussed in Chapter 3) can be used to develop algorithms for different aspects of wireless sensor network where sensing accuracy is dependent on the distance of the sensing nodes from the point where the event is occurring in the monitoring area, such as target tracking, fire detection, surveillance etc. In this thesis, the sensing model has been applied to develop a target tracking algorithm (discussed in Chapter 7). Experimental results confirm the improvement and prove the effectiveness of the proposed sensing model. In this model, only five inference rules have been defined, based on which the target tracking algorithm is developed. Number of inference rules can be varied depending on the requirement of the application. The inference system does not compute the exact Euclidean distance. Effective distance encompasses all the uncertainties in measurements such as the presence of obstacles, anisotropic media, signal scattered by dust or other type of suspended particles, etc. Thus the fuzzy inference system qualitatively defines the sensing coverage or in short the coverage of individual node and the network as a whole.

Depending on the requirements of the application, number of inference rules are used. If an application demands more accuracy, more number of inference rules can be defined. Similarly, if an application requires lesser accuracy and to lower the complexity of the algorithm, a smaller number of inference
4 CONTRIBUTION OF THE THESIS

rules can be defined.

A fuzzy based communication model is proposed in Chapter 4. The contribution of this model is that it can also be applied to develop efficient algorithms for different problems of wireless sensor network applications such as clustering, localization, routing, surveillance, overhearing etc., to improve the performance in terms of battery energy and other application-specific measures. This model has later been successfully applied to develop i) clustering algorithm and ii) localization algorithm. The simulation results of these algorithms confirm the usefulness of this model. In this model, also only five inference rules have been defined, based on which the clustering and localization algorithms are developed. Number of inference rules can be varied depending on the requirement of the application. Here also the effective distance will not be the Euclidean distance. This distance takes into account the uncertainty in result due to the presence of different obstacles, multi-path fading etc.

A fuzzy based unequal sized clustering algorithm (see Chapter 5) has been proposed to improve the energy performance and to solve the hot spot problem mentioned earlier. The algorithm is based on the fuzzy communication model (Chapter 4) proposed earlier in the thesis. The proposed algorithm not only uses the remaining battery energy of the nodes to rotate the election of cluster heads but also uses another important factor ‘how long a node remains unused as a cluster head’. Use of this factor helps largely to reduce the probability of a node to be chosen as a cluster head frequently. Simulation results for different cases show significant improvement in the lifetime of the sensor network in terms of first node failure (FNF), half node failure (HNF), and last node failure (LNF). For example, the proposed algorithm is compared with HEED [56] and UHEED [13] and the results are as follows: FNF values are 459 rounds using proposed algorithm, 266 for UHEED and 265 for HEED, whereas, corresponding HNF values are 2553, 972 and 1043 rounds for the proposed algorithm, HEED [56] and UHEED [13].

Chapter 6 proposes a fuzzy based range free algorithm to determine the location of sensor nodes. The proposed algorithm uses neither any special hardware device such as a GPS module nor any computation intensive parameters such as Angle Of Arrival (AOA), Time Of Arrival (TOA, or Time Difference Of Arrival (TDOA) (as mentioned in Section 3). The algorithm applies the fuzzy communication model (Chapter 4) successfully. Extensive simulation has been done and the corresponding results confirm the significant performance improvement in terms of accuracy of the result as well as energy usage. For example, the average values of the localization error obtained for the proposed algorithm is 0.3657 and that for centroid method is 2.2082 whereas the maximum value of it is 1.1302 for the proposed algorithm and 4.6533 for centroid method.

The thesis is also contributed to another very important application of WSN that is mobile target tracking (discussed in Chapter 7) and proposes a fuzzy based solution for this problem. The algorithm forms a convoy tree around the target as soon as the target is visible and follows continuously as it moves within the monitoring field. The algorithm achieves 100% coverage, thus, improves the tracking accuracy (accuracy of collected information about the target). Using fuzzy sensing model (as in Chapter 3) and following an event driven scheme, the algorithm not only runs faster but also improves the energy usage. A real WSN composed of TelosB motes is set up to test the proposed algorithm. Experimental results thus obtained shows a substantial improvement in performance in terms of energy usage. As for example, when the target moves at 8m/s speed, the energy usage for joining and pruning of nodes for sparse deployment is 0.039 mW and for DCTC is 0.41 mW. Similarly, the same in dense deployment is 0.124
mW for the proposed algorithm and for DCTC it is 0.64 mW.

5 Organization of the Thesis

The contributions of the thesis are organized as follows.

Chapter 1 provides the introduction of the thesis. The chapter identifies wireless sensor networks and its architecture. The chapter discusses the architecture of individual sensor nodes. Chapter describes different applications and challenges exists in designing any application. The chapter also discusses the motivations behind this work and the contribution of the thesis toward the challenges.

Chapter 2 performs an elaborate survey of the on-going research activities on the related topics. Current researches on the development of models on sensing coverage and communication coverage of wireless sensor network has been done in detail. Similarly, a detailed review has been performed on some of the challenges of WSN, such as clustering, localization and target tracking.

Chapter 3 presents a fuzzy logic based model for the sensing capability of sensor nodes. A fuzzy inference system is introduced. Fuzzy input and output variables and their relationships are identified, the membership functions and their probable values are also introduced. This chapter also introduces some measures for sensing coverage to quantify the performance.

In Chapter 4 the fuzzy communication model is elaborated in detail. The chapter discusses the fuzzy inference system, input-output relationships and the nature of the membership functions of each variable and how to choose the controlling parameters of these membership functions. This chapter also introduces the concept of fuzzy neighborhood, and fuzzy connectivity and proposes some measures to quantify the process.

Chapter 5 introduces a clustering algorithm. The algorithm is based on the fuzzy communication model of Chapter 4. The proposed algorithm tries to optimize the usage of battery energy using fuzzy technique. The chapter defines a fuzzy inference system which takes i) “remaining battery energy (remainEnergy)” and ii) “number of times a node remains unused (timesUnUsed) as cluster head” or “connector” as two inputs to calculate the rank of each node. This rank is heavily used in the algorithm to select cluster heads to reduce the energy demand of the network. The algorithm also tries to solve the hot spot problem of clustered networks by using fuzzy unequal clustering technique.

Chapter 6 deals with the localization problem of WSN. The proposed algorithm is based on the fuzzy communication model discussed in Chapter 4. The work introduces a range free fuzzy localization algorithm. Also, it elaborates the fuzzy inference system used and shows the performance improvement over some existing algorithms.

Chapter 7 introduces a fuzzy based target tracking algorithm. The algorithm is based on the fuzzy sensing model of Chapter 3. Another fuzzy inference system is proposed that helps to create and maintain a convoy tree around the target within the field. The tree provides 100% coverage to ensure data reliability.
and at the same time optimize the energy demand using very few reconfigurations of the tree.

Finally, Chapter 8 concludes the thesis. This chapter outlines the research topics, discusses other challenges exist and the new challenges coming due to the emergence of new application area. Based on these challenges the chapter finally draws the roadways of future research directions in wireless sensor network.

6 Conclusion

In last few decades, Wireless Sensor Network (WSN) has gained huge attention by the research community as well as application developers. Research on this subject has unlocked the possibilities of numerous new applications. Due to the use of battery operated tiny sensor devices, wireless sensor network poses myriad of challenges to the application designers. Among the challenges, battery power conservation comes to the top of the list. Analysis shows that the most energy consuming areas of WSN application are i) sensing the physical events ii) communicate gathered information about the sensed event to the sink node. Apart from energy conservation, two other important problems are maintaining good coverage and connectivity. So understanding this two behavior of wireless sensor nodes are very important and needs to develop efficient models for these. These models can further be used to develop algorithms to solve different problems of wireless sensor network. In this thesis, two such models are proposed and few problems are chosen, such as clustering, topology control, target tracking and localization, where the mentioned models are applied successfully. The results of simulation and experiment show a significant improvement of the situations over the existing ones.

Future direction of work can be data compression, data fusion and data prediction techniques to reduce energy usage. Routing is another important issue. Developing a suitable lightweight operating system is another challenge to the research community. Cross layer optimization has the huge potentiality to improve the situation.

References


REFERENCES


REFERENCES


Publications

Journals


Conferences


