Using Wireless Sensor Networks for Fire Rescue Applications: Requirements and Challenges

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***Abstract*— Research in wireless sensor networks has attracted a lot of attention in recent years. Real applications, such as habitat monitoring, environmental and structural monitoring, start to work in practical. In this paper, we argue that wireless sensor network is a very promising technology for fire rescue applications. First, we abstract four specific requirements of this application, including *accountability of firefighters, real-time monitoring, intelligent scheduling and resource allocation,* and *web-enabled service and integration*. To meet these requirements, we propose FireNet, a wireless sensor network architecture for this specific type of application. Based on these requirements and the characteristics of wireless sensor networks, several research challenges in terms of new protocols as well as hardware and software support are examined. Finally, we conclude that wireless sensor network is a very powerful and suitable tool to be applied in this application.**

I. Introduction

As new fabrication and integration technologies reduce the cost and size of wireless micro-sensors, we are witnessing another revolution that facilitates observation and control of our life and physical world [2], [5] just as networking technologies have done for the ways individuals and organizations exchange information. Networks of interconnected tiny sensors deeply embedded into the physical environment enable us to observe and interact with the environment and human beings in real time in a fidelity that was previously unobtainable. Recent advances in both sensor hardware, e.g., Motes from Crossbow [4], and software, e.g., TinyOS [10], have enabled the fast growing of real sensor network applications, including habitat monitoring [12], environment sampling [3] and structure monitoring [13], showing the promising of wide applications of wireless sensor networks (WSN).

This paper proposes to apply wireless sensor networks to a very important public safety activity — fire rescue application. We argue that this is a promising application of WSN based on the analysis to the abstracted application requirements and the characteristics of WSN. The rest of the paper is organized as follows. First we describe a typical scenario of state-of-the-art of fire rescue operation, and abstract four specific requirements of the fire rescue application in the rest of this section. Then we propose an architecture of wireless sensor network called FireNet in Section II. In Section III we examine the research challenges on design and implement the proposed FireNet infrastructure from the perspective of protocols, software, and hardware challenges.

A. Fire Rescue: State-of-the-Art

Fire rescue is one of the most important public safety activities. A typical scenario of the fire rescue process is depicted as follows. After a fire department gets a fire alarm call, it will send a fire rescue team to the fire field. Normally, a fire rescue team consists of one incident commander vehicle, two engine vehicles, one ladder vehicle, and the most important role, a set of firefighters, who are grouped as squads associating with one of the above vehicles. During the process of fire rescue, the incident commander is in charge of the whole fire rescue situation, including monitoring the fire field and making real-time schedule on firefighter assignment. The two engine vehicles carry water, which will be used in the case when water is lack near the fire field. And the ladder vehicle holds the utilities like ladders that are needed by the firefighters. The firefighters are organized into different squads based on their specialty and fight cooperatively to eliminate fire in the fire field.

This fire rescue operation mode has several shortages. First of all, the incident commander could not have a clear view of neither the status of firefighters after the rescue work starts nor the accurate situation of the fire field, so that it is difficult for him to make an optimized schedule. Second, the firefighters in the fire field do not know the dangerous situation around him in time, which increases the danger to the firefighter as well. Finally, it is inflexible for the fire department headquarter located far away from the fire field to get fresh and timely fire rescue information, which is particularly important for big cities which might have multiple fires at the same time.

Currently fire rescue may be supported by some systems such as Geographic Information System (GIS) [8] and FINDER [6]. For example, FINDER uses some technology to guide the fightfighter to find the injured crew members; however, the incident commander and fire department have no clear view of the whole fire field so that it does not help to make good schedule of fire fighting operation. GIS is another popular system used in the fire rescue applications. It allows a user to view and analyze information graphically and spatially, and maintain a database of that information. Thus, it is good in fire protection and management but not very suitable in applications that have high real-time requirements. GEOMAC [7] is a successful system built based on GIS to help fire rescue, which links the GIS technology to the Internet, using remote-sensing data from automated remote weather stations and some image-interpreting skills to provide managers the real-time information. However, this system does not monitor the ambient condition of firefighters, which is essential for a good fire rescue operation.

In summary, current fire rescue is not efficient and current fire rescue systems either focus on fire protection and management or focus on only guiding firefighters in an inefficient way. A more effective fire rescue system is necessitated to support on-site fire rescue. Before giving the details of the proposed architecture, we first analyze the requirements of this specific application.

B. Requirements

Wireless sensor networks are application-specific systems. Different applications may have specific requirements of the design of the underlying WSN, including protocols as well as the hardware and software support. Fire rescue is a special application which is different from the previous WSN-enabled applications, such as environmental or habitat monitoring, and object tracking, thus it has several specific requirements. In the following paragraphs, we will describe them one by one in detail.

- **Accountability of firefighters**. Accountability of firefighters is the first and most fundamental requirement of any fire-related public safety applications. Continuing with the basic scene of a fire rescue application described above, when firefighters start fighting in the fire field, the incident commander and fire department need the information of the firefighters, one of which is for the accountability of firefighters. At the current stage, each firefighter is associated with a squad and one vehicle. When the firefighters enter in the rescue operation, they leave their badges in the vehicle, which has their name and ID only. After firefighters come back from the rescue work, they get their badge back. If the badge is left in the engine, the incident commander assumes that the owner of the badge is missing in fire rescue. In this way, the firefighter will only have two status, alive or missing. As a matter of fact, this approach for accountability is too obsolete to collect useful information. We argue that for the complete accountability of firefighters, we need the following information of each firefighter, including both static and dynamic information. A list of static information could be *name, ID, age, specialty, primary squad assignment and second squad assignment*. Primary squad assignment denotes the squad the firefighter belongs to in the normal condition. And second squad assignment denotes the temporarily assignment of the firefighter to another squad to substitute some absent firefighter with the same specialty. Besides these static information, we would also like to know the dynamic information of firefighters in the field, such as the total time the firefighter participated in the fire rescue, the workload of the firefighter, continuous locations of the firefighter, and the physical condition of the firefighter. These information can be collected by WSN and reported to the incident commander, who will evaluate the efficiency of the fire rescue operation based on these accurate accounting information.
- **Real-time monitoring**. Besides the accountability information of firefighters, more real-time information about the firefighter and fire field is wanted by the incident commander and the fire department. First, the incident commander needs the real-time location information of firefighters, because the firefighters keep moving according to the fire situation during the process of fire rescue. Having the location information, the incident commander can make better schedule, e.g., he can find firefighters with some specialty and send them to where they are needed. In addition to the information about firefighters, the fire field information is also very useful for the incident commander to judge the real situation of the fire rescue and make real time decision and schedule. Thus, the WSN could be used to collect the environment information of the fire field, including *the humidity and temperature of the fire field, the wind speed, the density of the smoke,* and so on. Furthermore, the information about some vital events in the fire field need to be monitored as well, e.g., *the death of the firefighters and the dramatic changing of the environment parameters*, such as temperature, chemical and biological leak. Based on these information, the incident commander and fire department will have a clear view of the fire situation and make effective schedule to fight the fire.
- **Intelligent scheduling and resource allocation**. The quick changing of environment and the happening of emergent events in the fire field require that the fire rescue schedule is made in a timely fashion, in fact, which is very difficult, if not impossible, for the incident commander in current fire rescue operation. Thus, to improve the speed of response to the changing environment and emergency, we argue that an intelligent software, which capable of automatically mining the collected data, is essential to aid the incident commander and fire department to make quick but effective decision on how to fight the fire. The requirements of this software is listed as below. First, this software needs to analyze the information collected from the fire field, calculate the accountability, and detect the events. Second, it should present these data to the incident commander and fire department in an easily understandable way. Third, the software can automatically generate the schedule of fire rescue process based on the collected data. Finally, the software should notice the incident commander when some important events are detected. In WSN, this software will run either on the powerful laptop acting as sink deployed on the incident commander's car or on the machines located in

the fire department.

- **Web-enabled service and integration**. Not only does the incident commander sitting near the fire field need the information collected by the WSN, but also the officers sitting in the fire department, which is located far away from the fire field. In a big city like New York, there maybe several fires happened at the same time, so the officers in the fire department need to make schedule on how to control these fires effectively and concurrently. Thus the real-time information from different fire fields is needed by the fire department, and the optimized schedule will be made based on this global information. Web-based service is one of the most convenient ways to provide these information to these officers. By doing so, the real-time information from each fire field is wrapped as a web-enabled service, accessible through regular Web browsers. Because the fire department is located far away to the fire field, the traditional Internet will act as the bridge to connect the fire field and fire department. First, the web-enabled service should provide the information that the fire department interested via the network, e.g., it continuously report the live situation of each fire field. Second, it will automatically generate some events to the fire department to ask aid when more firefighters or vehicles are needed. Moreover, the collected data can be stored and analyzed later to find some good rescue models to support the future fire fight.

II. FireNet Architecture

Having known the requirements of the fire rescue application, we are now in a position to propose FireNet, a wireless sensor network architecture for the fire rescue application.

Compared with traditional wired sensor systems, the novelty of WSN lies in that the sensors deployed in the sensor field can self-organize into a connected ad-hoc network via wireless communication. We call the specific wireless sensor networks deployed for the fire rescue application FireNet. The architecture of the FireNet is shown in Figure 1. In the FireNet, the vehicles and firefighters are equipped with sensors which form a self-organized heterogenous wireless sensor network. In the incident commander's vehicle, a powerful laptop connected with a powerful sensor acts as the gateway of WSN. The ladder vehicle and the two engine vehicles are loaded with sensors having GPS equipped. These vehicles can act as the landmark for the whole WSN because they will have relatively stable location, i.e., other sensors can calculate their location based on the location of these vehicles. Each firefighter in the sensor field carries a sensor, such as MICA2 or MICAz from Crossbow [4] attached with available sensor board which can sense interested parameters, acting as the *active badge* for each firefighter. The active badge records all the information expected by the incident commander and fire department (for later analysis), such as the firefighter information, the fire field environment information and emergent events, as listed in the Figure 1. The role of each active badge (i.e., sensor) has two-fold: sensing the data and forwarding the packets. We can also install different program on the sensors for the firefighters with different specialty, thus these sensors can have different functionality. Furthermore, the sink of FireNet, located in the incident commander's vehicle, is connected to the fire department headquarter via traditional Internet so that the WSN and the fire department can communicate each other and keep contact.

After the fire fight team starts their work, the sensors attached to vehicles and firefighters are self-organized into a WSN via wireless communication. Then, the sensors start to operate according to their pre-installed program. For example, the sensors attached to firefighters will collect the information of firefighters, sample the environment parameters, and generate the vital events happened in the fire field, as shown in the right part of Figure 1. These data will be reported to the sink by the multi-hop routing protocol and further delivered to the fire department via Internet. Then, both the incident commander and the officers in the fire department have the accountability and real-time information from the fire field, which is abstracted and presented by the powerful pre-installed software in the sink or fire department. By doing so, the whole fire field is monitored and the status of each firefighter is clear to the incident commander and fire department. Based on this, the incident commander and fire department will make optimized fire schedule according to the suggestion of the intelligent software. For instance, in the case of fire rescue in September 11, 2001, some firefighters were covered by the dust or buried in some part of fire field of ground zero, which is a very dangerous situation. If WSN is used, it will be much easy to detect such a situation and the location of firefighters in danger, a rescue can be arranged immediately to help them out of the disaster. Moreover, the schedule commands from the incident commander can be sent to firefighters via FireNet to instruct the firefighters to move or take some other actions as well.

In addition to the communication ability, each sensor has its CPU and local memory so that it can do some calculation such as data aggregation and store the data for a period of time. With the development of the semiconductor technology, the computational capability and the memory size have been extended a lot in the last several years. We believe that wireless sensors will be more powerful in the near future so that more information can be stored and more efficient real-time decision making algorithms can be employed. In summary, as described above, wireless sensor network is a very promising technology in the application of fire rescue. It is very useful in terms of not only monitoring the whole fire field including the firefighters and environment information, but also sending schedule information and commands to the firefighters in a more intelligent way.

III. Research Challenges

As described above, the fire rescue application has its special characteristics, such as high mobility and real-time, and specific requirements as described in Section I-B. Previous protocols are not satisfactory and need to be revisited for this

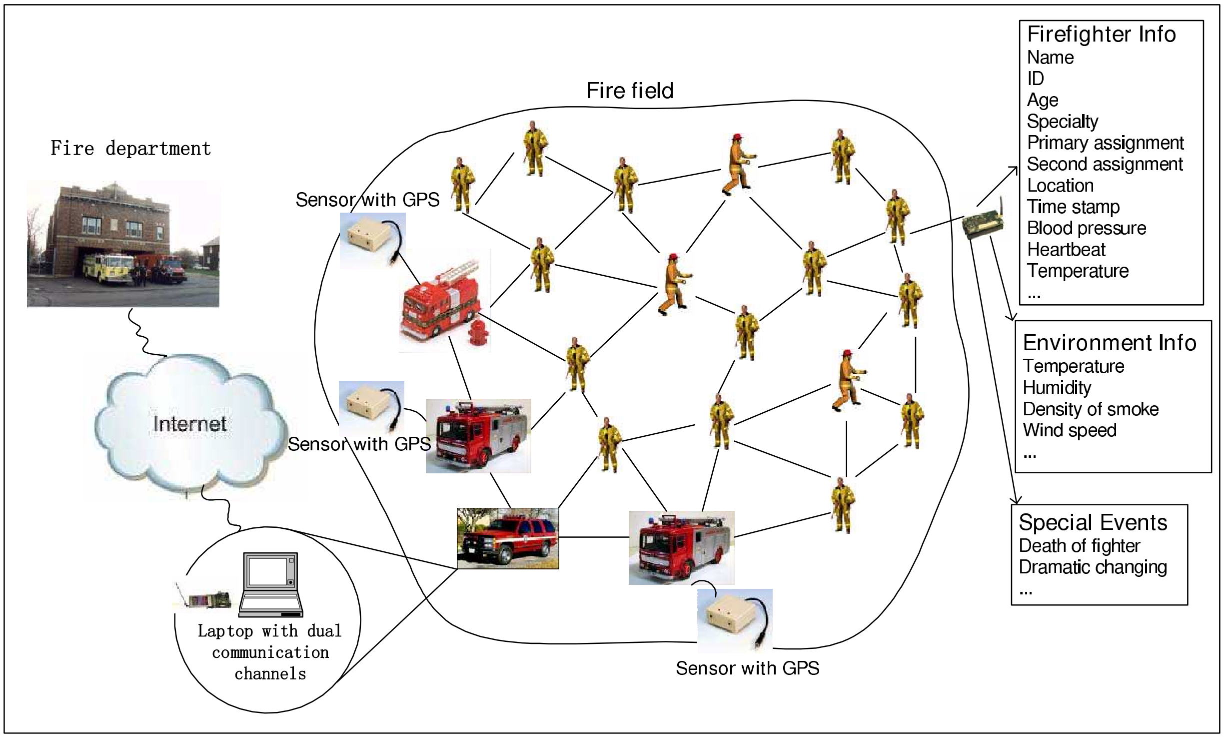

Fig. 1. The architecture of FireNet.

application. New protocols and support from hardware as well as software are needed to build the sensor system. Next, we narrate them in detail.

A. Protocol Challenges

First, four protocol challenges, namely *real-time self-organization, fault-tolerant routing, service differentiation,* and *real-time and mobile localization*, need to be addressed for this application.

- **Real-time self-organization**. FireNet is a pure ad-hoc wireless network, thus the self-organization of FireNet is very crucial. Unlike other WSN applications like environment monitoring, the fire rescue application of WSN has two specific characteristics, the high dynamics of sensors due to the high mobility of firefighters in the fire field, and the real-time requirements of data collection. These two inherent features make the self-organization of FireNet become more challenge. Moreover, we expect that the wireless communication between sensors in a fire field has extremely high loss rate due to the harsh environment. Thus, it is not easy to achieve the goal of real-time self-organization. A good self-organization protocol should be proposed to support the automatic re-configuration of the sensor network, which should have the capability to make all the sensors attached to firefighters and other utilities in the sensor field connect or re-connect to the sensor network in a limited period of time after they newly join the network, lose the connection and reconnect, or change their location. In such a protocol, several functions are highly wanted. First, the relationship between each firefighter and his/her associated vehicle should be captured automatically; Second, in a short period of time after firefighters start the fire fight process, these firefighters and the utilities are all self-organized into a connected ad-hoc WSN; Third, during the procedure of firefighter moving, the sensor network should keep connection in spite of the absence of several firefighters from their original area, and the moving sensors should re-connect to WSN in a limited time at the new location. The challenge of this protocol lies in how to satisfy the real-time requirement, and always keep the connectivity and coverage of the whole WSN.
- **Fault tolerant routing**. As argued above, one significant characteristic of the fire rescue application is the high dynamics of network resulting from the mobility of firefighters or failure of sensors. Although the real-time self-organization protocol takes care of the re-configuration of WSN, it cannot assure the successful delivery of messages to the sink. However, the fire rescue application has high requirement on accuracy and real-time to the collected data. A fault tolerant routing protocol is essential to guarantee the successful delivery of the data and events in the case that the mobility and absence of some sensors as well as the unreliable wireless communication will cause a high package lost rate. The fault tolerant routing protocol should deal with both the mobility of sensors and the failure of sensors happened in the sensor field in a timely fashion. Previous research on the routing

protocol [1] in WNS usually assume that sensors are located in fixed position, neglecting the high dynamics of the network. Thus, novel routing protocols are expected to handle the problem of sensor mobility and real-time delivery. One possible solution is to build multi-path routing protocols in the real time, which can dramatically improve the probability of successful delivery in a high dynamic environment.

- **Service differentiation**. The main function of the WSN in this application is to collect different information from the fired field, e.g., the environment parameters such as temperature, humidity, wind speed, and chemical and biological leak, the emergent events such as the dramatic changing of the environment parameters and the death of firefighters, and the status of the firefighters such as location, and the workload of firefighter. Although all these data need to be monitored and collected, their importance is different and then these parameters should be treated in a different way in the system. Thus, we argue that an efficient service differentiation scheme, including timeliness, storage requirement, and processing priority, should be provided to implement multiple quality-of-service (QoS) in such an environment. As a matter of fact, how to arrange the collection and delivery of these data in an effective and efficient way is a challenge because sensors have limited low bandwidth and share the wireless communication medium. A good service differentiation scheme is needed to schedule the data collection and transmission through the FireNet architecture. One possible direction is exploiting the inherent consistency requirements of those parameters. For example, an event of firefighter death is much more important than any other parameters in the network, so it will be set the highest priority and reported to the sink as soon as possible. In addition, the tradeoff between the energy efficient and data consistency including data accuracy and timeliness should also be examined in the protocol.
- **Real-time and mobile localization**. As we described in Section I-B, the location, especially the real-time location, of firefighters in a fire scene is a very important and valuable piece of information. Given this piece of information, the incident commander could have a clear view of the distribution of deployed firefighters, and make real-time decisions. Moreover, location information is very useful for other protocols in WSN as well. Most research topics in WSN, e.g., fault tolerant routing, aggregation, event detection and tracking, and so on, directly or indirectly lend on accurate location information provided by the underlying localization service.

  Admittedly, location in the fire rescue application is not a trivial task given the fact that firefighters are moving very fast and randomly in a real rescue operation as well as the inherent ad-hoc feature of FireNet. Localization in WSN has been extensively studied in the literature [11]; however, as a reality check, few of practical localization algorithms are deployed in the real applications, and practical localization, especially mobile localization, is still a challenge from the perspective of real deployment. Intuitively, Global Positioning System (GPS) is a pretty good positioning system at outdoors, however, it is not accurate enough for indoor tracking. Moreover, most of existing localization solutions did not take the mobility into consideration, i.e., they always assume the location of sensors is static, which is obviously not the case in FireNet. The few mobile localization algorithms such as [9] do not consider the moving speed and the dynamics of the system.

  Therefore, we argue that the localization protocol for a WSN in fire rescue application needs to address the following issues: *mobility, heterogeneity, locality, robustness, feasibility,* and *accuracy*, each of which is described as follows.

  1) *Mobility* The fast movement of firefighters makes the localization a big challenge in a timely fashion.
  2) *Heterogeneity* Due to the heterogeneity of the sensors used in FireNet, the localization algorithm should take these diverse platforms into consideration, e.g., the computing devices on some vehicles/equipments, such as laptops or tablets, could be integrated with GPS support which provides some reference points for further location resolving, while on the other side, the sensors carried by firefighters would be very simple and possess only limited computing resource and energy support.
  3) *Locality* Each sensor has limited computing power, memory, and communication range, thus only a completely localized algorithm is applicable in FireNet, where each sensor interacts with its neighbors only.
  4) *Robustness* Sensors in FireNet are working in a very harsh and highly failure-prone environment. Robustness is a key requirement of the localization algorithm, i.e., the failure of some sensors should not affect the calculation of other sensors location.
  5) *Feasibility* The localization algorithm has to be practical enough so that its computing cost could be affordable by the limited hardware/software supporting of those tiny sensors.
  6) *Accuracy* The real scheduling by the incident commander and fire department is based on the accurate location of firefighters. Accurate positioning in a static environment is already nontrivial, it becomes more challenge in such a highly dynamic environment.

B. Software Challenges

As analyzed in Section I-B, software components are required in the sink and fire department. These software components are used to analyze the collected data and make good schedule suggestion. Because the sink and fire department have different requirements to the software, two types of software should be designed for them respectively.

The software for the sink should has the following functions. First, it needs to analyze the collected data and abstract the useful information from the data such as the accountability information of each type of firefighters. Second, it should make some schedule suggestions based on the collected data and some preset rules. Third, it needs to present the abstracted information and the schedule suggestion to the user of this software. The design of this software includes two parts, the graphic user interface (GUI) part and the intelligent decision making and scheduling part. All the information needed by the incident commander and fire department will be presented in the GUI interface. For instance, the accurate real-time location of firefighters will be shown in a map of the fire field. And the accountability information as well as the status of firefighters will be provided by the GUI. The scheduling part has the function of analyzing data and generating schedule suggestion. A well designed rule set is essential to provide good scheduling schemes. Some technologies from artificial intelligence community may be useful to design the rule set through self-learning. Besides, to support the remote access of these real-time information, we need to provide a web-enabled interface, which needs to take the security into consideration because of the confidential information of firefighters.

Another software component is needed at the fire department side. We can use the similar software as in the sink. However, the officer in the fire department may not care such detailed information as a incident commander. For them probably the general information is enough. Meanwhile, the decision rules at the fire department are different from those of a incident commander. Comparing with the incident commanders, the officers in the fire department headquarter need to re-schedule the firefighter squads as a whole across multiple fire fields.

C. Hardware Challenges

The fire rescue application also posts some specific requirements on the hardware support for sensors. Normal commodity-of-the-shelf wireless sensors, e.g., motes from Crossbow [4], are applicable in this application in terms of functionality. However, to our knowledge, they haven't considered the extremely harsh environment like fire field, which is a very important issue to the success of the WSN deployment. The FireNet architecture proposed for the fire rescue application is running in a dangerous environment which normally has fire, water, dust, and extremely high temperature. Moreover, the sensors are shaking and moving dramatically with the moving of firefighters. If the sensors are exposed to such an environment without well protection, it will stop working immediately. So we argue that two issues should be considered to address the hardware challenge. One is packaging, and we need to come out an ideal packaging scheme for sensors to make sure they are water-proof, fire-proof, and vibration-proof. The other is the internal design of wireless sensors. Some fault tolerance features should be taken into consideration during the design procedure.

IV. Summary and Future Work

In this paper, a new application of wireless sensor newtorks in the process of fire rescue is proposed and analyzed. Based on the analysis of specific requirements of the fire rescue application, we argue that wireless sensor network is very promising in this application and propose an architecture called FireNet. At the same time, we admit that there are still several research challenges need to be addressed before the real deployment of FireNet. Recently, we have started collaborating with the Detroit Fire Department to build a prototype of FireNet and hope to deploy a workable FireNet system in the near future.

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