Towards a Tailored Sensor Network for Fire Emergency Monitoring in Large Buildings

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***Abstract*— Modern fire emergency systems are slowly moving from the traditional data-logging systems to a heterogeneous and dense network of wired/wireless sensors that can give a more complete view of the phenomenon. When the density of the sensors and/or the transmission rate start growing, standard and widely used communication protocols suffer from degradation in their performance, mostly due to the presence of simultaneous transmissions. Rather than proposing a new protocol that performs better than the standard ones in a set of network scenarios, this paper has a different aim. It attempts to draw conclusions from the nature of the sensed data itself, so that important spatial and/or temporal correlations can be revealed and, consequently, utilised for the future design of an indoor fire emergency-tailored protocol.**

I. INTRODUCTION

The present view of fire emergency communications, where traditional data-logging systems are deployed for data acquisition from sensors, is changing. Fire engineers are considering alternative methods for super-real-time prediction of fire propagation with the aim of providing accurate information about the fire evolution and egress to the fire brigades. Apart from the existing infrastructure of point smoke detectors, a pool of heterogeneous sensors is envisaged, such as smoke/CO detectors, heat flux meters, thermocouples, pressure gauges, cameras etc., which will sense and convey the necessary information to the fire model [1].

Although the existing wired infrastructure can serve as the wired backbone or backup route if the wireless links fail to survive the extremely harsh fire conditions, practical reasons, such as ease of deployment, low cost and straightforward reconfigurability, have recently led to the consideration of wireless sensor networks for many structural health monitoring applications [2]. However, although wireless sensors are a very promising solution, there are still many research and implementation challenges. Depending on the application, i.e. whether it is aiming for a specific small/large scale fire test or for an actual long-term deployment in a large building or power plant, there are several issues to be overcome: tradeoffs between a denser and, thus, more reliable and robust sensor architecture and collisions caused by simultaneous transmissions, fast and accurate delivery of important messages, such as fire alarms, and also power depletion of the wireless sensors. Being a part of the FireGrid [1] project, this work aims to examine the potential of replacing the traditional use of the bulky and expensive data-logging systems with wireless sensors for small and/or large scale fire tests.

Rather than exploring general solutions to the problems described above, this paper takes an application-driven approach, i.e. it tests the hypothesis that the properties of the network traffic caused by a test or a real fire can be exploited to assist the communication protocols in the Medium Access Control (MAC) and the routing layer, with the timely and accurate transfer of data to a sink. Let's consider a building with multiple compartments, in one of which a fire starts and then spreads to other rooms. Ideally, the sensor network would signal the occurrence of the fire and collect enough data to identify the strength and the rate of spread of the fire, smoke and toxic gases to other rooms, and also enable prediction of events like the time to collapse of the building. This will have to be achieved by a dense array of sensors in each compartment. A combination of a dense sensor network and a frequent sampling proves to be quite a challenge for standard communication protocols, as will be shown shortly. However, it is noticed that during a fire, field variables, such as gas temperatures are highly correlated, both in the space and the time domain. These inherent statistical properties of the considered signals can guide in the design of the protocol.

The impact of correlations on the design of sensor networks has been studied in the literature. [3] proposes a mathematical model that yields large synthetic traces of data from a small experimental trace, while preserving the correlation pattern. In [4], the performance of three routing and compression schemes is analysed with respect to the joint entropy of the data sources. Dimensions [5] is a data storage and querying algorithm suitable for habitat monitorin, that exploits spatial correlations. Correlations across sensor arrays have also been studied in the fire research community, but in a different scope, e.g. fire localisation [6]. Finally, in [7], CC-MAC protocol selects a subset of the sensor nodes for data generation in order to reduce contention. CC-MAC assumes that the correlation structure of the network is mainly a function of the physical distance and is known to the sink in the deployment stage of the network; therefore, it is not very suitable for fire emergency applications, where correlations may change rapidly and do not only depend on physical proximity.

This paper does not make the usual assumptions about the distribution of data like the majority of researchers [3]. It utilises information generated from fire simulations employing zone models [8]. Its main contribution is to demonstrate that the hypothesis of a stationary correlation structure [7] depending only on physical distance is not accurate for a fire emergency application. In fact, fire data exhibits dynamic behaviour regarding the spatial correlations and the time development of the phenomenon. These remarks can be used as guidelines for the design of a fire-emergency centric communication protocol. The rest of the paper is organised as follows: Section II introduces the model used for the fire simulation and the scenarios considered. In Section III the networking simulation framework is described and the performance of a standard sensor network protocol is shown. Section IV discusses the spatial and temporal correlations of data generated from the simulated fire scenarios and provides basic protocol design guidelines, then Section V concludes the paper and sketches the future work.

TABLE I
SENSOR NETWORK PARAMETERS USED IN SIMULATIONS.

MAC & PHY layer	IEEE 802.15.4
Beacon and Superframe Order	3
Routing Protocol	DumbAgent,AODV
Propagation Model	Shadowing
Path Loss Exponent	3
Transmission Rate	250 Kbps
Frequency	2.4 GHz
Transmission Current Drain	17.4 mA (0 dBm)
Reception Current Drain	19.7 mA
Idle State Current Drain	20 μA
Receiving Threshold	-94 dBm

II. FIRE MODEL AND SCENARIOS

The nature of the considered application is highly dynamic. Consider an array of thermocouples monitoring the temperature of each compartment in a building. Suppose a fire starts in one room, the hot gases and smoke rise and a smoke layer begins to envelop the room. Eventually, the smoke and hot gases reach the other compartments and, if the temperature is high enough, may ignite combustible materials present in the other rooms. This causes an escalation in the quantity of the vital information to be transmitted. In this work, we consider some well documented scenarios of growth of a fire in several multi-compartment buildings [9]. Actually, in such a building there is great variability in the spread of the fire, as its characteristics depend on the burning material, the arrangement of combustibles and the ventilation characteristics. Due to the enormous combinatorial complexity, the enumeration of all possible scenarios is infeasible; one needs to restrict to a limited set of scenarios that would still provide useful statistical properties of the data source (i.e. spatial and temporal correlations that typically occur among the temperatures in the rooms).

A zone model called CFAST [8] is used to predict the spread of the fire. In a zone model, each room is split into two zones with temperature being uniform in each zone. The top zone consists of the high

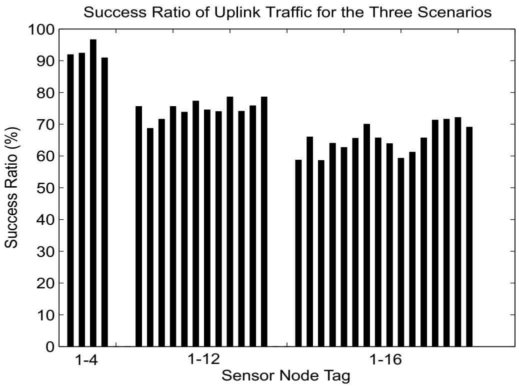

Fig. 1. The ratio of data packets delivered successfully to the sink.

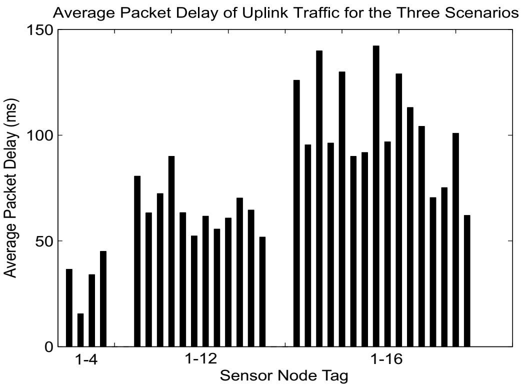

Fig. 2. The average delay of the successfully delivered data packets.

temperature gases and smoke, while the lower layer consists of lower temperature gases. The height of the interface between the two zones is called the smoke layer height and this layer descends as smoke builds up in the room. Therefore the temperature is always a step function with a jump at the location of the smoke layer height. The scenarios considered are documented in [9]: (i) a single room geometry, (ii) a three room geometry with a fire originating in one room and spreading to the other two rooms and (iii) a four compartment geometry with analogous behaviour. Each compartment is equipped with a vertical array of thermocouples, located in heights 2.0, 1.5, 1.0 and 0.5 m above the floor and in the centre of each compartment.

III. FRAMEWORK FOR THE WIRELESS SENSOR NETWORK SIMULATION

It is assumed that the thermocouples (sensing unit) are connected to Mica-Z [10] wireless motes, whose basic parameters are summarised in Table I. The propagation model adopted in the network simulations is shadowing with a path loss exponent of 3[1]. A vertical array of four equispaced sensors is placed in the centre of each room for all the three scenarios. The sink is mains-powered and is located at the edge of every topology furthest to the ignition source. The usual precision monitored by data-loggers is 6 digits, therefore 20 bits are needed for their representation. Moreover, fire tests usually timestamp the sensor data; this adds a further 64 bits (using the enhanced Unix time representation) to the data payload size. Therefore, the minimum payload size (reserving the remaining 4 bits e.g. for power monitoring) is 11 octets. In accordance to fire tests conducted in FireGrid, the rate of the uplink traffic, i.e. from the wireless motes to the sink is 1 sample per second.

The wireless motes are running IEEE 802.15.4, and AODV (Ad Hoc On-Demand Distance Vector) as the routing protocol. Actually, most real applications support ZigBee routing, a combination of AODV with clustered routing, which we are currently developing in NS2. Each test lasts for 2000s; throughout this interval, the ratio of data packets successfully delivered to the sink and the average packet delay are measured. The results are presented in Figs. 1 and 2. The cluster of bars 1-4 refers to the single compartment scenario, the sensor tagged as 1 being the closest to the ceiling, the cluster 1-12 to the three-room test, with the sensors counting from room 1 and going to room 3 and, finally, the cluster 1-16 refers to the four-room test.

It is evident from the graphs that, as the network becomes denser, the presence of more simultaneous transmissions sharing the same wireless channel causes the performance of the communication protocols to degrade, i.e. the ratio of successfully delivered data packets to drop and the average transmission delay to increase. Analogous behaviour was observed when no routing protocol was selected (selection of DumbAgent in NS2). Consequently, even in relatively small-scale fire tests the protocols seem to not be able to deliver accurately and timeously all the sensed information for a relatively high transmission rate. This fact may be vital when important events, such as fire alarms need to be

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[1] This is a crude estimate for same-floor office rooms [11]. In our future work, we will investigate the incorporation of more refined indoor pathloss models, so that open/closed doors can be represented.

TABLE II

CORRELATION COEFFICIENTS

Window (s)	Room 1	Room 2	Room 3
1-10	0.89-0.79-0.65	0.79-0.79-0.79	1.00-1.00-1.00
11-20	1.00-1.00-0.23	0.43-0.99-0.99	0.47-0.77-0.77
21-30	1.00-1.00-0.99	1.00-0.92-0.92	1.00-0.93-0.93
31-40	1.00-1.00-0.98	1.00-0.99-0.99	1.00-0.98-0.98
41-50	1.00-1.00-0.95	1.00-0.99-0.99	1.00-0.87-0.99
51-60	1.00-1.00-0.99	1.00-1.00-1.00	1.00-1.00-0.99
61-70	1.00-1.00-1.00	1.00-1.00-1.00	1.00-1.00-1.00
71-80	1.00-1.00-1.00	1.00-1.00-1.00	1.00-1.00-1.00
81-90	1.00-1.00-1.00	1.00-1.00-1.00	1.00-1.00-1.00
91-100	1.00-1.00-1.00	1.00-1.00-1.00	1.00-1.00-1.00

conveyed to the sink.

IV. STATISTICS OF THE FIRE SENSOR DATA AND COMMUNICATION DESIGN GUIDELINES

Temperature data is obtained from CFAST for three scenarios of the fire igniting in room 1 and moving to the other compartments. Due to the physical proximity of the sensors and the dynamic nature of the fire, the sensed data is not independent throughout the test. The metric adopted to evaluate the correlation properties of the data is the correlation coefficient f defined as

$$f = \frac{E[(T_i - \bar{T_i}) \cdot (T_k - \bar{T_k})]}{\sqrt{E[T_i^2] - E^2[T_i]}\sqrt{E[T_k^2] - E^2[T_k]}}, \qquad (1)$$

where T_i is the temperature of thermocouple i, and $i \neq k$. Table II shows the correlation coefficient between the top sensor of the vertical array and the three lower ones for each of the rooms of the three-compartment fire simulation. The first column depicts the time window where the correlation is computed and the other three columns the coefficients for (T_1,T_2)-(T_1,T_3)-(T_1,T_4) respectively. The initial 100 seconds of the fire simulation are used, since they correspond to the most demanding stages of fire growth and the signalling of an alarm.

Observing Table II, it seems that there are times during the fire spread where the correlations between sensors of each room are very strong. Consequently, the simultaneous transmission of their sensed values would not benefit the fire modeller, but only cause unnecessary burden to the communication protocols. On the contrary, there are periods when they are much lower. These correspond to the instances where the transmission of the sensed data must be as refined as possible. For example, in room 1 where the ignition occurs, the only such interval is the first $10s$, where the smoke layer is on the top and there is not much association with the lower thermocouples. From that point on, the smoke layer descends fast and the whole room can be perfectly represented by a single transmission[2]. Interestingly, the time periods of the lowest redundancy of the data are different for each room and follow a time-sliding effect corresponding to the 'front' of the fire.

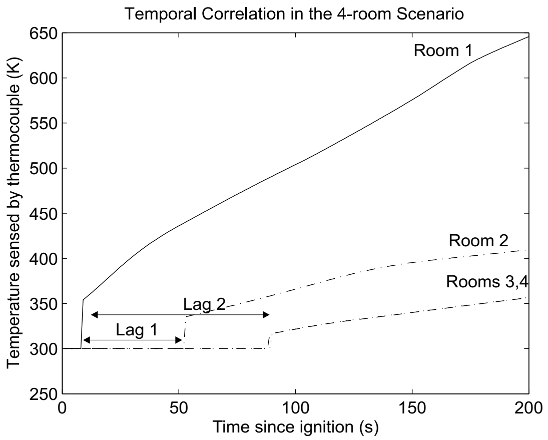

Fig. 3. This figure shows the lags between the time instances where critical data needs to be conveyed to the sink for each of the 4 rooms in the third scenario. The fire ignites in room 1, spreads into the corridor (room 2) and then moves on to both rooms 3 and 4, symmetrically located with respect to room 2. The values shown correspond to the highest thermocouples in each room, but analogous observations can be drawn for all sensors in each vertical array.

The latter observation is verified when examining closer the temporal evolution of the sensed temperature readings for the third scenario, i.e. the four-compartment building. As is depicted in Fig. 3, there is a critical lag between the time when sensors of room 1 need to alert the sink about temperature rise, and the time when sensors from other rooms need to do likewise. Should in this critical interval all the sensors be concurrently transmitting at the same rates, collisions might impede the accurate and timely delivery of data. On the other hand, should the sensors of rooms 2,3,4 be idling or transmitting at a reduced rate right after this critical interval,

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[2] Note that perfect correlations among the sensors seen in Table II are an artifact of the zone model, for which all the sensors within a zone measure the same temperature. However it is reasonable to expect that even in a real fire, the thermocouples measuring the temperatures in the upper hot region or the lower cooler region would be correlated to some degree as well. This has been verified by various initial experimental data that have not been reported here due to space constraints.

then vital information might be lost. Therefore, it is evident that it would highly benefit the design and/or optimisation of a sensor data dissemination protocol to be able to take into account the nature of the fire data and try to quantify the qualitative conclusions drawn in this paper.

Key features of a suitable algorithm that follow from the discussion above are summarised below:

- Main aim of the algorithm should be the dynamic selection of a suitable subset of sensor nodes that can convey the information sufficient for the fire modeller to the sink.
- The protocol should not require neither complete nor *a priori* knowledge of all data source correlations at each sensor and at the sink.
- Clustered architectures are highly suitable for indoor sensor networks. However, the optimal size and layout of clusters should depend on their correlation structure.
- Finally, a probabilistic scheme is necessary, that will dictate the activation of sensors in the proximity of the 'front' of the fire so that necessary fire alarms are not missed or delayed. Statistical methods such as change point detection techniques seem suitable for this purpose.

V. CONCLUSIONS AND FUTURE WORK

This paper aims to set the ground for the design and optimisation of a communication protocol specifically tailored to successfully deliver time critical information in the case of an indoor fire emergency situation. The trend of the fire research being to use increasingly dense sensor grids for increased spatial resolution, issues such as the concurrent transmission of data to the sink from multiple sources are proved to cause severe performance degradation, even in medium-sized buildings. However, from data generated from simple zone models for compartment fires, it is shown that there exist spatial correlations in various periods of the fire growth, which can be exploited from the network protocols, so that unnecessary transmissions do not impede the transfer of critical information.

As on-going work, more refined fire models are going to be used (e.g. field models), in combination with actual experimental fire test data, for a more complete study of the related phenomena. The scenarios will be expanded to large buildings or power plants of realistic size, tested with a variety of sensor network protocols. Finally, and more importantly, the basic guidelines mentioned above are going to be used for the design of a fire-centric data delivery system for indoor applications.

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