

Design Issues of an Operational Fire Detection System integrated with Observation Sensors.

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Abstract: Operational design issues for the development of an innovative early warning automatic fire detection/surveillance system are introduced. The basic blocks and high-level architectural concept of the terrestrial components integrated with state of the art satellite data handling and earth observation resources and sensors are defined and analyzed in a consecutive fashion. Furthermore distributed detection strategies of fire events given hardware and communication limitations are extensively discussed and reviewed. In this context special attention is given to connections with First Responders technical data communication issues and other critical subsystems including current high priority design challenges. Further research directions are suggested for the integration of technological platforms with future aerial and space based sub-systems within the proposed hybrid model.

Keywords: Fire Detection System; Wireless Sensor Networks; High Level System Architecture; Decentralized Detection; First Responders Communications; TETRA Interoperability, Earth Observation; UAV.

1. Introduction

For the past decades large scale devastating fire events have been occurring in the Mediterranean region. In particular the wider region of Greece has a history of severe fire crisis amounting to devastating damages to property, ecology and losses of civilian lives. High and often abrupt climate variations, hot dry winds, the global warming changing conditions as well as organized criminal activities are the main causes of severe and multiple fire breakouts. These events have resulted in serious crisis situations which often have been developed into natural disasters. Thus, fire events put in danger not only the existing ecological stability of large geographical areas of the country, but also the security of hundreds or even thousands of civilian lives, see also (Marke, 1991) for cable tunnels and his overview of the level of Telecom Australia's operations.

One of the most challenging and serious problems during the evolution of a forest fire is to obtain a realistic and reliable overall common operational view of the situation under development. Combating fires with large fronts is an extremely difficult and dangerous task due to high and abrupt changes of wind direction and intensity, high spatial and temporal variations as well as due to the high variety of forestry and natural vegetation of the environment. In that respect reliable early warning and suppression of fire outbreaks is of paramount importance. Great efforts are made nationwide to achieve early forest fire detection based mainly on human surveillance. These activities are usually organized by the Greek Fire Brigade which is a governmental authority in conjunction with volunteer local private organizations. It is evident that this kind of effort which is based basically on human observation is problematic. Moreover it usually takes place during the summer season between the months of June and September. Our main motivation relies on the fact that to the best of the authors' knowledge at least on a national level there is no operationally sustainable and dedicated sensing network capable of providing reliable early detection and surveillance services to the authorities and public entities. In that respect there are no realistic past data or previous operational experience with similar deployed

architectures for fire prevention and monitoring. Another motivation is the recently completed Greek pilot project called: Satellite - based FirE DetectiON Automated System (SFEDONA) which was funded by ESA under ARTES -34 framework (SFEDONA, n.d.; Liolis et al., 2010). For our work we are using as a starting step the basic architectural concept of this project and we proceed further providing an analytical and coherent operational system enriched and extended with Earth Observation components as well as with First Responders critical operational communication sub-systems.

The purpose of this chapter is threefold: At first to introduce commercially available H/W modules that will be useful for fire prevention and monitoring, thus minimizing human intervention actions. Secondly to provide the designer and /or policy maker with some available results from the field of distributed detection theory and how associated methods may be taken into consideration during the initial design phase of the S/W application modules. Thirdly to provide some state of the art technological platforms based on existing and future aerial and space based subsystems that could be properly integrated in the proposed hybrid architecture. In this line and for completeness some important First Responders' open technical communication problems are introduced relating interoperability issues with other existing broadband services. Specific issues related to TETRA communications architectures (Terrestrial Trunked Radio) which are highly critical to the operational capabilities of the search and rescue teams are raised and analyzed. Thus the main contribution of this chapter is the conceptual presentation of an extended operational early warning - monitoring and fire detection system applied but not limited to the Greek situation.

In section 2 some design specifications of the building blocks and subsystems including the satellite communications backbone provided by HellasSat are presented. Further description of the hardware and software components integration is presented in section 3 combined with existing decentralized and sequential detection strategies. A detailed account of the state of the art decentralized approaches in conjunction with some useful fundamental statistical aspects are given adapted to the hybrid model. Different technical limitations imposed during the design and implementation stage are highlighted and presented in section 4. In section 5 some critical operational issues related to communications interoperability between First Responders networks are presented. The integration framework of aerial and space based earth observation remote sensing components with the proposed model is analytically provided in section 6. High-level research directions and guidelines in integrating the proposed architecture with advanced existing and newly developed European space based tools are provided in section 7. It is noted that the introduction and review of the most recent and future technical advancements concerning space based tools in fire and disaster crisis monitoring is presented focusing on the technical efforts of the European Space Agency and the European Community. These efforts are discussed aiming to pinpoint at specific directions for the implementation of an innovative, operational and most importantly sustainable solution. In section 8 the final conclusions of this work are provided.

2. Description of basic system architecture

The proposed model combines terrestrial and space based infrastructures and sensors (SFEDONA, n.d.; Liolis et al., 2010). The terrestrial part is comprised of four general hierarchical levels:

1. The End - Users Fixed Common Operational Center
2. The Remote Fusion/Decision Central Node (**R-F/D-CenN**)
3. The Remote Data Collection Nodes (**R-D/C-N**) and
4. The Set of Environmental Sensors (land based event observers).

The Common Operational Center (CoC) is the public entity or surveillance authority responsible for the coordination and supervision of the overall fire crisis management tasks. The space-based components consist of the Data Handling subsystem (HellasSat) and the Earth Observation infrastructure feeding the Center with all necessary remote sensing earth observations.

The terrestrial platform basically consists of the following IT and Hardware components:

1. **Pan-Tilt-Zoom (PTZ)** cameras combined with the set of environmental sensors and local weather monitoring stations installed at remote and isolated critical areas of interest.
2. **Satellite Communication Network** based on the DVB-RCS standard along with the installation of the respective satellite terminals for the interconnection of the fixed CoC and the various **Remote Fusion/Decision Central Nodes (R-F/D-CenN)**.
3. **Earth Observation Imaging Data** processing units located at the Operational Center premises.
4. **Wi-Fi** access points (Wi-Fi AP's) for the interconnection of the wireless sensors and PTZ cameras with each one of the **Remote Data Collection Nodes (R-D/C-N)**.
5. **Zig-Bee** (IEEE 802.15.4 standard protocol) - to - **WiFi** (IEEE 802.11) gateways providing links between the ZigBee network of the wireless environmental sensor set and the rest of the WiFi network.
6. **Independent Power Supply Units** (such as small Solar Panels) for the energy powering of the **Remote Data Collection Nodes (R-D/C-N)** and the **Remote Fusion/Decision Central Nodes (R-F/D-CenN)**.

The above system components combine standard protocols with available Commercial - Of - The Self (COTS) products. A careful selection must be made so that various performance criteria and trade offs are met such as:

interoperability, quality attributes, format of the component, necessary physical resources for the functioning of each device component, technical limitations and restrictions, capacity, size, performance specifications, data handling etc.

The IEEE 802.15.4/ZigBee protocol for Wireless Sensor Networks allows fast, scalable and easy network deployment and adoption supporting QoS combined with COTS devices and technologies. It is known that the IEEE 802.15.4 Data Link/ZigBee network layer, allows the implementation of three network topologies - Star, Mesh and Cluster- Tree - while ZigBee defines 3 types of devices: ZigBee Coordinator (ZC) -ZigBee Router (ZR)- ZigBee End Device (ZED), see for more details (Cunha et al., 2007; Da Silva Severino, 2008). It is noted that a key feature of the IEEE 802.15.4 Data Link/ZigBee devices is the classification into two subcategories: The Full Function Devices and the Reduced Function Devices. The later are End Devices implementing only very simple (reduced) applications such as infrared passive sensing (IR passive sensor devices) transmitting very small amounts of information in the sensor network. Thus they are very beneficial in terms of low power consumption since end - devices can be asleep for long periods of time and can wake up only when it is needed for data transmission.

In the sequel various software component applications are proposed to run on the sub-systems such as:

- Application to run at the Common Operational Center premises for continuous monitoring, surveillance and control of the remote geographical regions.
- Application to run at the Operational Center for immediate alerting of the end-users in case of fire breakouts. An integrated powerful Geo-Spatial Information Subsystem (GIS-subsystem) for fire representation and spreading is proposed to support decision making on the part of the end-users, indicating the exact location of the fire events using available vector/raster background maps.
- Intelligent Software application to run locally at the Remote Fusion/Decision Central Nodes for event - observation and fusion of critical heterogeneous data coming from different sensing sources such as wireless PTZ cameras and the Remote Data Collection Nodes. Additionally advanced intelligent software applications will be necessary for decentralized event detection, and fast decision policy making.
- Application to run at the Remote F/D Central Nodes for critical data and fire alarm communication/transmission to the CoC.
- Application to run at the Remote Data Collection Nodes for simple local decision-making and message re-transmission. This type of node due to more relaxed power constraints compared to the set of environmental sensors' stringent power constraints, should be capable of more advanced signal processing/decision capabilities on a local level.

The selection criteria of the software components regarding intelligent algorithms for observation fusion and fast event detection is probably one of the most challenging tasks for this type of distributed networks. Several design and modeling issues related to this problem are addressed and discussed in the sequel. Additionally various performance indexes are introduced for performance evaluation of the detection algorithms. A short review of the current literature results and design efforts of intelligent decentralized detection is provided.

3. Analytical component description

As it is seen in Fig.1 below the basic component blocks are:

1. **The Satellite link:** This link provides a two-way data transmission with high reliability between the Remote Fusion/Decision Central Nodes located at the geographical areas of interest and the CoC which is located at the end user's location (village municipality or city). Both terminals operate in dual mode (receive and transmit) were for fire event detection and alerting the uplink data transmission from the Remote F/D Central Node to the CoC is of primary importance. For the Greek *terrain* and *environment* the baseline scenario involves the communications infrastructure concerning the GEO Ku-band satellite HellasSat2 at 39 deg. E. and its operational network which is based on the Digital Video Broadcasting-Return Channel via Satellite (DVB-RCS) standard. HellasSat owns and operates the Hellas Sat-2 geostationary satellite which provides IP and DVB services and thus will establish the backbone satellite communications link. In case of fire events detection and alerting data, messages are transmitted to the end user via the satcom interface. For the purpose of an alert verification or fire in progress situation, a low frame rate video stream can be transmitted to the site of the end user. A relatively low data rate satellite link is required and an assumption of 512/256 Kbps is reasonable.
2. **Remote Sensing:** Remote Sensing coupled with advanced information, telecommunication, and navigation technologies contributing to high-speed geo-spatial data collection more efficiently than ever, and supporting the disaster management organizations to work with higher volumes of up to date information. Fire imaging from remote platforms can be used in emergency response for strategic and tactical operations. Strategic observations are provided mainly by polar orbit satellite systems like NOAA/AVHRR, MODIS, ENVISAT, etc. These observations are in different spatial and spectral resolutions, and give a regional view of fire occurrences with time intervals ranging from some hours to one day. These observations are useful for disaster coordination support but are ineffective for repetitive timely observations due to orbit cycles. On the other hand tactical operations, which need real time

observations, are efficiently served by the geostationary orbit satellites like the Meteosat Second Generation, as well as airborne (manned or unmanned) platforms that are able to provide continuous coverage and rapid data accessibility over the entire country and individual fire events respectively. Among the most enduring data flow bottlenecks existing today are the challenges for interoperability during the operations, where space/airborne remote sensors need to work together with in-situ sensor networks and data fusion and processing nodes as it is proposed in our network architecture.

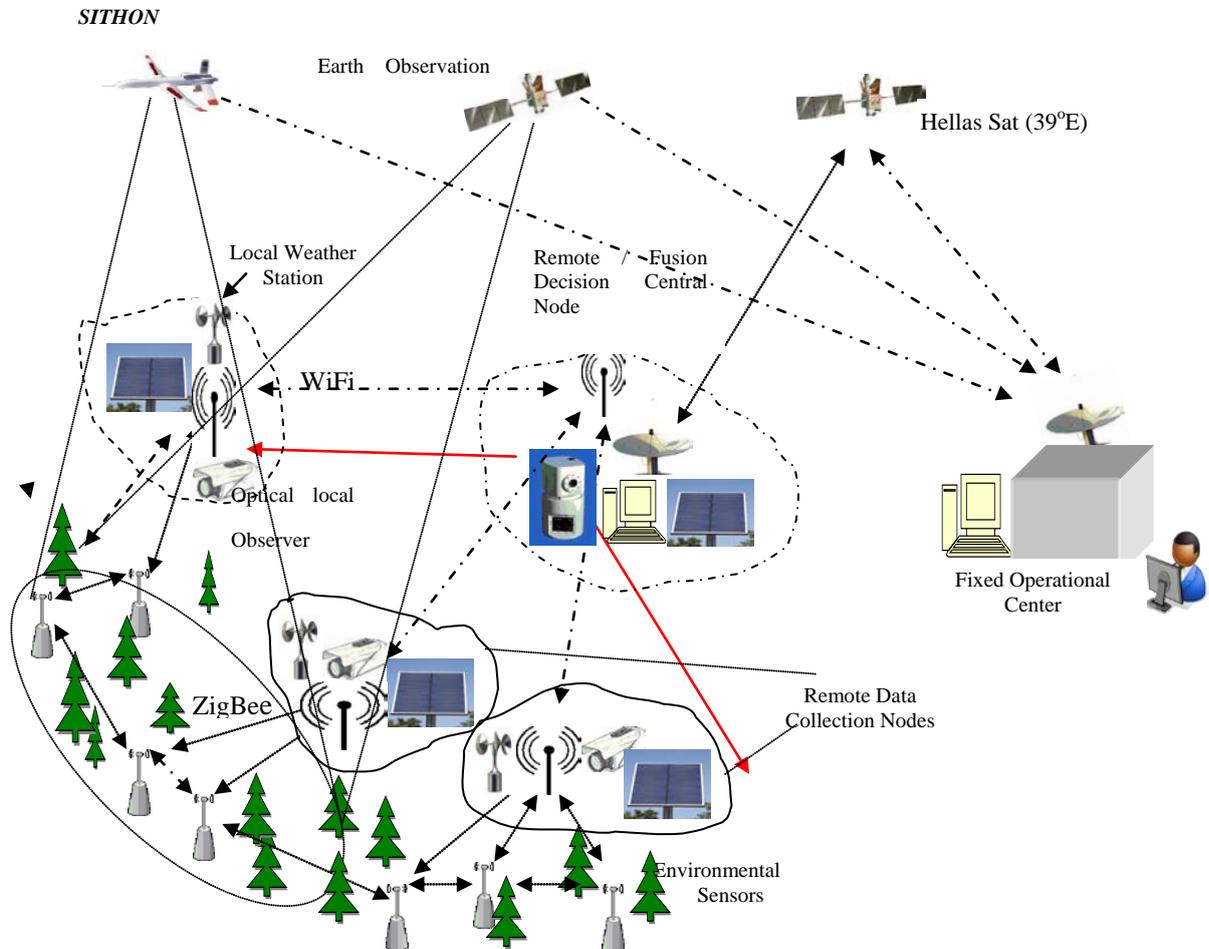


Fig. 1. Early Warning and Fire Detection Physical Model Architecture

3. **Common Operational Center site:** The fixed CoC is located at the end user's location (municipality, community or village site) and consists of an integrated S/W platform. The platform is responsible to provide common operational and continuous centralized and remote monitoring of the critical areas that are under surveillance and inspection. Moreover in case of fire detection or alarm signaling the CoC immediately is informed with the support of an integrated GIS - application for the indication of the exact location of the fire event with the aid of available digital maps of the region. The S/W application will include fast intelligent computational algorithms for real time estimation of fire front propagation based on inputs streaming from the environmental wireless network (**Remote Fusion / Decision Nodes**). Additionally the end users will be able to remotely control the PTZ cameras installed at the Remote F/D Central Nodes. In that manner continuous monitoring of the critical geographical sectors will be possible through video sequences/frames coming from the on field camera sensors. A satellite terminal also is needed to be installed providing satcom links between the field and the CoC.
4. **Remote Fusion/Decision Central Node (R-F/D-CN):** The remote fixed fusion/decision central node will be physically located at a safe distance from the critical area of interest such as a forest or an area of high probability for

a fire event to occur. It is responsible mainly for data fusion and decision-making as well as for alert distribution. It is noted that the final decision-making process and strategy for event detection is taking place at this Central Node by performing a probabilistic likelihood ratio test. It is based on the received observations and partial local type decision outputs of the Remote Data Collection Nodes. In that respect decentralized detection is of major importance and it is comprised of two main parts, see (Fellouris & Moustakides, 2008; Chamberland & Veeravali, 2007):

- a) The sampling strategy at the remote sensors (Event Observers).
- b) The detection policy at the fusion - decision center which in our case is the Remote Fusion / Decision Central Node.

Policies related to sampling rates basically define the type of sensor data that is transmitted to the Remote Fusion/Decision Node while policies related to detection concern the utilization of the transmitted information by the Fusion/Decision Node such as the final decision of the occurrence or not of an event. Sampling/detection strategies performed at the fusion center is a discipline of ongoing research efforts. The concept of decentralized detection was first introduced by (Tsitsiklis, 1993) and later by (Veeravali et al., 1993). We mention that for the centralized detection case the fusion center has complete access to the continuous time process observations which in our application set up is the fire event spatio-temporal evolution. Additionally one or (usually) several R-F/D-Central Nodes may be installed depending on the geographical region and terrain morphology.

Analytically the following components are required:

- A satellite terminal so that communication between the Remote - F/D - Central Node and the Operational Center is possible.
- A WiFi access point with its integrated controller so that communication between the various heterogeneous data coming from optical cameras, environmental sensors and small local weather monitoring stations is achieved. The link is based on the IEEE 802.11/WiFi family standards for short/medium range communications at the frequency of 2.4 GHz. The data rate can be up to 25 Mbps.
- A panoramic PTZ camera which will act as a redundant fire detection and surveillance device adding additional degrees of freedom to the overall architecture. As soon as the distributed sensors such as the optical cameras, the local weather stations and the environmental sensors generate an alert of a fire event, the end user can remotely point and zoom the PTZ camera to the specific site thus getting a better and fullest picture of the situation. PTZ cameras have the technical ability to pivot on their horizontal and vertical axis (pan/tilt head) allowing the users to cover and survey the areas of interest. Also they have an automatic setting allowing for scanning on a predetermined axis.

Some technical specifications are given depending on the product type and cost (COTS):

- Horizontal scanning ability of 340 deg. and vertical scanning of 100 deg.
- Motion sensors.
- IR sensitivity for scanning at nighttime or areas of low light.
- Ethernet cable connectivity.
- Up to 45 frames/sec at a resolution of 640x480.
- JPEG & MPEG encoding.
- An integrated S/W application so that data fusion and decision policy tasks are possible. The input to the F/D central node includes all available information generated from the sensing hardware such as optical cameras, environmental sensors and the local weather monitoring stations. Moreover this S/W application will be responsible for data and alarm transmission to the Operational Centers' site.
- An independent power supply unit. It is necessary since the Remote -F/D-Central Node will have to be autonomous and as it is mentioned will be located at strategic geographical areas of possible high-risk fire events. In that way independence from the power grid is achieved. The power unit is proposed to be based on relatively small solar panels, including charging battery arrays, inverters and controllers, so that autonomous operation is achieved for several days.

5.Remote Data Collection Node (R-DC-N): It is the basic Data Node responsible for collecting the various data sequences transmitted from the local optical cameras and environmental land based sensors and for performing the real-time local sensing of the fire event. There can be one or more data collection nodes depending on the application and geographic location or sector and will be located near or inside the critical areas in fixed positions. Moreover an additional assumption is made that these nodes are capable of re-transmitting an amplified version of its own local partial observation and local decision of the events at the remote central node. Thus the remote data collection nodes act in the network as amplifiers transmitting sequences of finite alphabet messages to the Remote Central Nodes. Furthermore each node consists of the following sub-systems:

- A WiFi access point with an integrated controller for the communication between the Remote Data-Collection Node and the Remote F/D Central Node. The Data collection node will be collecting all available data from the sensors: optical camera, local weather monitoring stations, and the environmental sensors and feed them to the Remote F/D Central N. The interface data rate can reach up to 25 Mbps.
- Wireless optical cameras or "Optical Observers" responsible to perform real time local detection of fire-smoke-flame parameters. It is proposed that embedded image processing algorithms are included or further developed

depending on the morphological terrain. The operation of these “Optical Observers” is mainly based on low-resolution high dynamic range contrast camera providing robust representation of an event or scene under various uncontrolled illumination conditions. Reliable and advanced image/signal processing algorithms can be implemented either of the self (COTS) or by in house development. The range coverage of each camera will be in the order of a few Kilometers. For, each Data Collection Node four “Optical Observers” suffice to cover wide geographical regions (>30 km).

- A remote weather monitoring local station attached to the mast of each sensor - optical camera capable of collecting and monitoring local weather information such as: Wind direction and speed, humidity factors, air temperature variations, dryness etc. Such an “instrument” will add extra degrees of freedom and reliability when combined with the optical “Observers” and the environmental field sensors. It will provide valuable information related to the status of a potential fire event or even further to provide critical information for fire front prediction and progress. The proposed weather stations will be able to transmit data to the Remote Fusion/Decision Central Node via the WiFi access point (Wi-Fi AP) of the Data Collection Node.
- A Zig-Bee (IEEE 802.15.4) to WiFi gateway which will be attached to each optical camera. It can act as a local coordinator of the ZigBee network of the environmental sensors that are associated with a specific camera. Basically the gateway establishes a bridge between the ZigBee network topology of the environmental sensors installed in the distant area and the Remote Data Collection Node. In that way critical data coming from the installed wireless sensors can further be communicated via the WiFi wireless interface to the Remote F/D Central Node. The interface data rate can be up to 115.2 kbps from the ZigBee side and up to 25 Mbps from the WiFi side.
- An independent Power Supply subsystem. By definition and due to the distant location, functionalities and hardware limitations, the Data Collection Node will have to operate autonomously with no human intervention and totally independent of the power grid network. The operation will need to be proper and seamless for long periods of time. In that respect this power subsystem will provide power to the components of the Node such as the WiFi access point, the optical sensors, the remote local weather station and the ZigBee to WiFi gateway. A solar panel based power system is proposed that is similar to the one mentioned for the Remote F/D Central Nodes. However since there will be no satellite terminal at the site of the Data Collection Node the power specifications and constraints can be significantly relaxed.

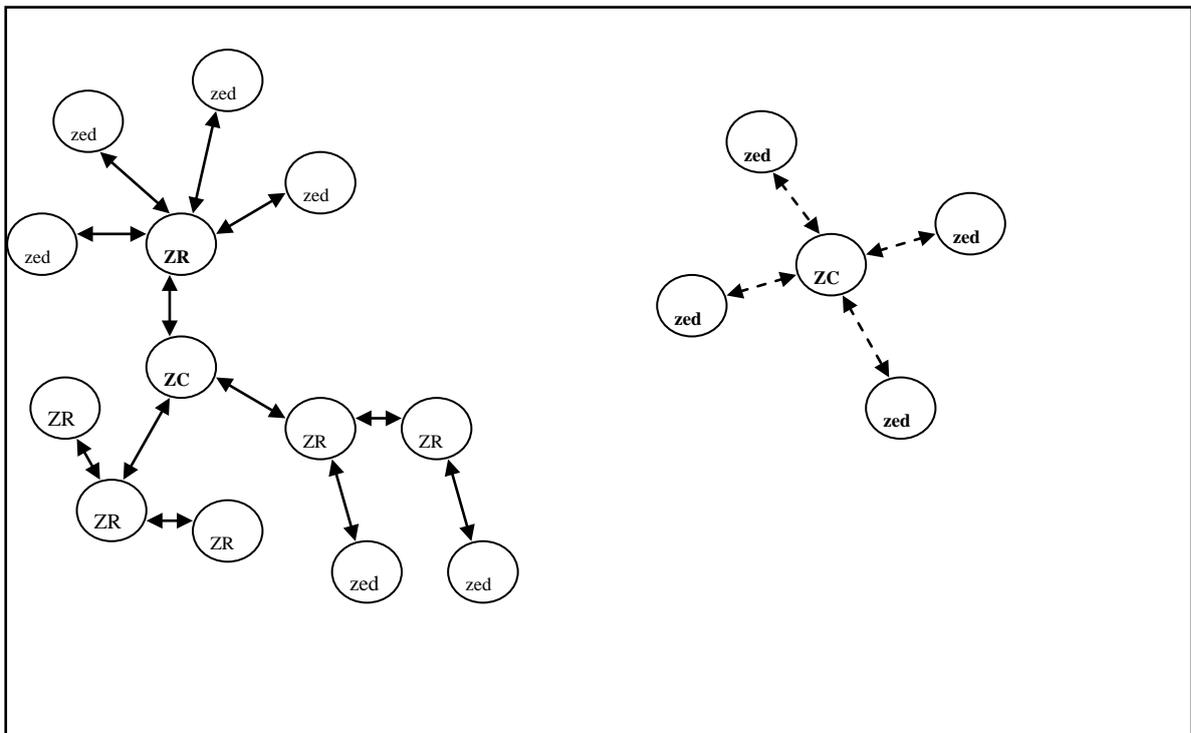
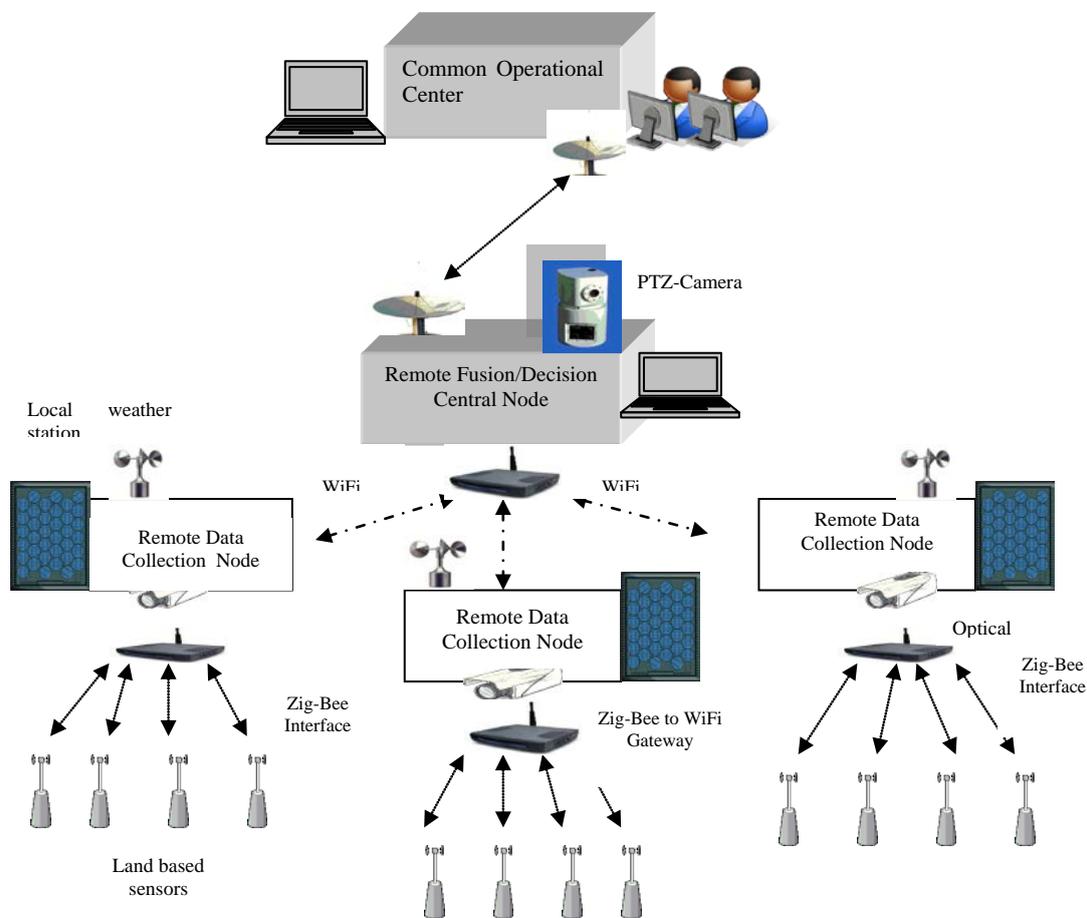


Fig. 2. Zig-Bee typical Cluster – Tree and Star network topologies

• The wireless local environmental sensors that are distributed in the areas of interest measuring parameters such as humidity, smoke, flame, temperature or soil moisture. These sensors are low cost, low power and small size wireless devices capable of having communication links between them at low data rates via the ZigBee wireless network interface. The density of the distribution (distance between the sensors) strongly depends on the morphological terrain of the critical site of interest. A typical distance could be 1 km in the field areas. Communication of the environmental sensors with the rest of the network is feasible using the Zig-Bee to WiFi gateway which is attached to each optical camera installed at the Data Collection Node. Finally an option for the installed sensors could be the family of Low Power RF transmitters. With respect to the three known Zig-Bee topologies star-mesh-cluster-tree as are shown in Fig. 2., for the application of fire detection the selection should be made between the mesh and cluster/tree topologies since cluster/tree topologies provide higher network flexibility, and are more power efficient using battery resources in a more optimal fashion.

An important performance testing parameter to be accounted for in the specified network application is the “smooth” coexistence of WiFi/ZigBee technologies since they both operate at the same 2.4 GHz band. For example minimization of interference risks is of paramount importance since it has been observed in various applications that ZigBee can experience interferences from Wi-Fi signal traffic transmission (some packet losses due to increased WiFi power levels). Careful field testing investigation is required when employing the wireless network to evaluate and confirm the coexistence limits of both types of RF based technologies.

In the following Fig. 3., a Top Level - schematic geometry of the early warning architecture is presented. The Earth Observation components are excluded for simplicity reasons.



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Fig. 3. Block interface schematic diagram of the proposed model without the earth observation components

4. Distributed event detection strategy methods

For distributed land based sensor networks related to fire detection and environmental monitoring the event can be characterized as rather infrequent. In that setting surveillance is highly required while reliability and timeliness in decision-making is of paramount importance. Thus decentralized rapid detection based on fusion technology and intelligent algorithms play a key role in the proposed model (Gustaffson, 2008). In particular decentralized detection is an active research discipline imposing serious research problems and design issues, [Basseville & Nikiforov, 1993; Chamberland & Veeravali, 2006, 2007) and (Tsitsiklis, 1993; Veeravali et al., 1993). In the proposed application low cost flame, smoke, and temperature detectors as well as additional local environmental sensors to be employed are subject to various power limitations. The classical concept of Decentralized Detection introduced by [22] considers a configuration where a set of distributed sensors transmit environmental finite-valued messages to a fusion center. Then the center, is responsible for the decision making and alerting while the classical hypothesis testing problem is solved deciding on one of the two hypotheses, that are “*a change has occurred*” or “*a change has not occurred*” see (Gustaffson, 2008).

In our operational application, the decision on the type of data and alarm sequences to be sent to the Common Operational Center is primarily realized at the Remote Fusion/Decision Central Node (Global Decision Maker) since the Remote Data Collection Node acts more as a concentrator of field data capable of taking some kind of partial local decisions. It is noticed that the proposed model is decentralized in contrast to traditional centralized configurations where each distributed sensor communicates all observation data to the fusion center (most optimal case but with no design constraints). Moreover it is assumed that all data collection nodes can take decisions using identical local decision rules (Chamberland & Veeravali, 2006).

As stated in (Tsitsiklis, 1993), decentralized schemes are definitely worth considering in contexts involving geographically distributed sensors. Also in (Chamberland & Veeravali, 2006), it is explicitly stated that the basic problem of decentralized inference is the determination of what type of information each local sensor should transmit to the fusion center. It is evident that efficient design of a sensor fire detection/surveillance network depends strongly on the interplay between data compression, available spectral bandwidth, sensor density of the network and resource allocation, observation noise, and overall optimal performance of the distributed detection process. Moreover for the decentralized case the collected observations are required to be *quantized* before transmitted to the central fusion node. These *quantized* measurements then belong to a *finite alphabet*. This procedure as it is mentioned previously is the result of a combination of technical specifications such as stringent communication bandwidth and high data compression. For the proposed system each sensor transmits its own partial observation parameter such as smoke or flame, to the Remote F/D Central Node and thus it is sub-optimal when compared to centralized schemes where the central node has direct and full access to all observation sets. Careful and detailed analysis is necessary for the adoption (or in house development) of intelligent algorithms at the remote central fusion decision node.

Moreover realistic assumptions need be taken into account related to the shared medium or the so-called common wireless spectrum. As it is pointed out, in (Imer & Basar, 2007), several performance design challenges need to be combated when designing wireless networks such as limited battery power, possible RF interference from other sources, multipath effects etc. The restriction on batteries life cycle of the low RF power transmitters or the power supply is of major importance and imposes severe limitations on the duration of time each sensor is going to be awake/on and the number of transmission cycles is capable of making. In our case Data Collection Nodes are autonomous and backed up by solar panel power devices. On the other hand the different low cost environmental sensors scattered in the remote areas impose hard power limitations. Issues such as Optimal Measurement Scheduling with Limited Measurements need to be considered when developing the detection algorithms both at the Fusion/Decision Central Node and at the CoC site. In (Imer & Basar, 2007; Fellouris & Moustakides, 2008), the problem of estimating a continuous stochastic process with limited information is considered and different criteria of performance are analyzed for best finite measurement budget.

At this point, we mention design issues imposed by channel fading and attenuation. In a realistic situation the quality of the communication channels between the environmental sensors and the remote data collection and fusion/decision units is affected and degraded by heavy environmental changes, bad weather conditions, heavy noise and disturbances, different SNR's, bad location dependent connections etc. Design parameters related to the channels state and fading level need to be included during the design stage, see for further details (Chamberland & Veeravali, 2006; Imer & Basar, 2007).

Another important twofold issue is the type of observations at the sensors and the sensor location and density. A popular assumption is that these observations (or data) are conditionally independent which might not hold if sensors are to be distributed with close proximity and high density in a specified area. In that scenario sensors will transmit observation data that are strongly correlated. Then the theory of large deviations can be employed to evaluate the performance of the network. In our case as it is previously mentioned the environmental sensors can be employed at least within a distance of a few hundreds of meters apart of each other. It is not well known a priori what distance will produce correlated or uncorrelated observations. This depends on how large the fire front will be or of the fire progress in general. As it is explicitly stated in (Chamberland & Veeravali, 2006) the optimal location of the sensor network before deployment requires careful analysis and optimization and it involves a design tradeoff between the total number of nodes and the available power resources/node of the network.

Furthermore a realistic assumption for the observation data is that they are conditionally independent and identically distributed see (Chamberland & Veeravali, 2006; Gustaffson, 2008; Basseville & Nikiforov, 1993) for further detailed exposition. Then assuming that there are resource constraints, optimality is assured using identical sensor nodes. Optimality under this type of condition is a positive fact since these networks are robust and easily implementable. In the figure below the *conceptualization of a decentralized detection model* is presented.

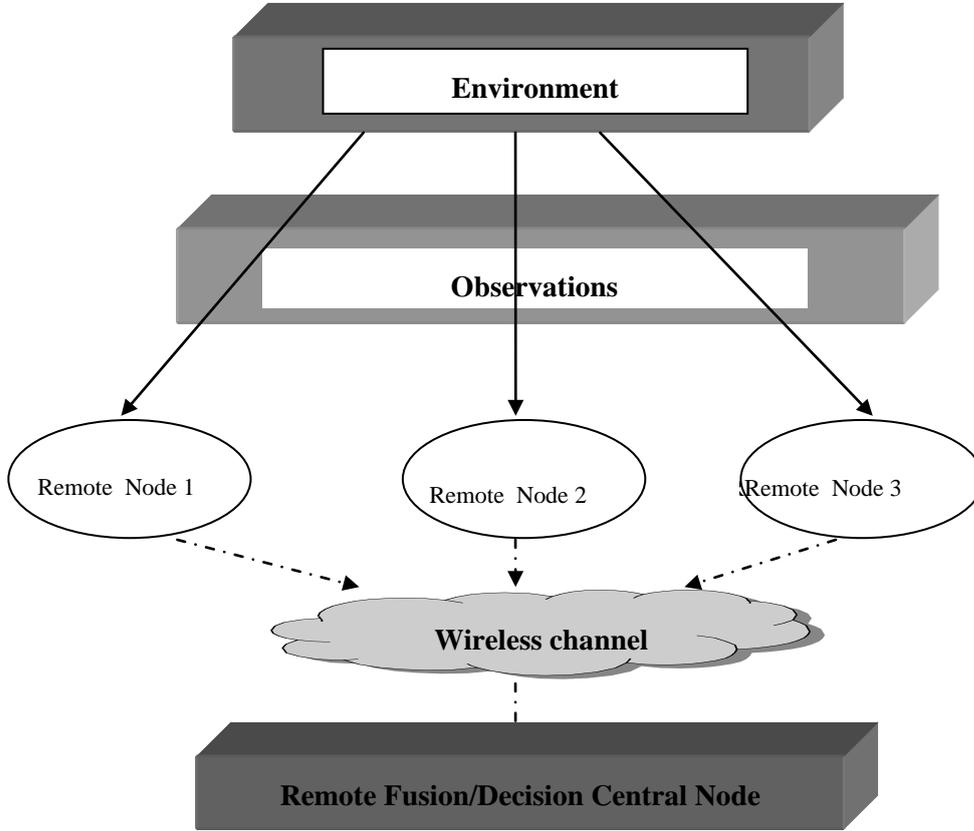


Fig. 5. Conceptual geometry of a decentralized detection model

It is evident that both the number of transmitted data per node and the number of available nodes is finite as well and the finite alphabet constraint is imposed on the output of each sensor. Then the basic problem that needs to be solved at the Remote Fusion/Decision Central Node is of a statistical inference type.

Another important design issue is that of decentralized sequential detection which for our system is carried out as previously stated at the Central Node. Sequential detection and hypothesis testing strategies involve deep mathematical results and various algorithms have been successfully applied in modern state of the art change detection and alarm systems.

In typical change point detection problems the basic assumption is that there is a sequence of observations of stochastic nature, whose distribution changes at some unknown time instant λ , for $\lambda = 1, 2, 3, \dots$. The requirement is to quickly detect the change under false alarm constraints. For the distributed case at hand, as it is shown in Figure 3, measurements are realized at a set of L distributed sensors. The sensor's outputs can be considered in general as multi-channel and at some change-point λ , one channel at each sensor changes distribution. Since sensors transmit quantized versions of their observations to the fusion center, change detection is carried out. At this point it is useful to mention some very basic facts and definitions related to On-line Detection. The subject enjoys intensive ongoing research since wireless and distributed networks are in fact gaining great popularity with an abundance of applications such as the one considered in this work.

Let $(y_k)_{1 \leq k \leq n}$ be a sequence of random variables with conditional density $f_\theta(y_k / y_{k-1}, \dots, y_1)$ and θ be the conditional density parameter. Before an unknown time of change t_0 the parameter $\theta = \theta_0$ (constant). After the

change time, the parameter θ assumes the value θ_1 and the basic detection problem is to detect this change as quickly as possible. Then a stopping rule is needed to be defined which is often integrated in the family of change detection algorithms. Moreover an auxiliary test statistic g_n and a threshold λ is introduced for alarm decision. The typical *stopping rule* has the basic form $t_a = \inf\{n : g_n(y_1, \dots, y_n) \geq \lambda\}$ with $(g_n)_{n \geq 1}$ being a family of functions of n coordinates and where t_a is the so-called *alarm time* that the change is detected see (Basseville & Nikiforov, 1993) for an extensive account. More formally the definition of a stopping time is the following:

A random variable (map) $T : \Omega \rightarrow \{0, 1, 2, \dots, \infty\}$ is called a stopping time if

$$\{T \leq n\} = \{\omega : T(\omega) \leq n\} \in \mathbf{F}_n, \quad \forall n \leq \infty, \quad (1) \quad \text{or equivalently}$$

$$\{T = n\} = \{\omega : T(\omega) = n\} \in \mathbf{F}_n, \quad \forall n \leq \infty \quad (2)$$

Notice that $\{\mathbf{F}_n : n \geq 0\}$ is a filtration, that is an increasing family of sub-sigma algebras of \mathbf{F} .

Finally five fundamental *performance criteria* are presented which have an intuitive reasoning to evaluate and assess change detection algorithms:

1. Mean time between false alarms,
2. Probability of false detection,
3. Mean delay for detection,
4. Probability of non-detection,
5. Accuracy of the change time and magnitude estimates.

Usually a global performance index concerns the *minimization of the delay for detection for a fixed mean time between false alarms*. For the proposed fire detection set up it is important that careful analysis of available sequential detection algorithms is performed taking into account the above criteria as well as the basic tradeoff between two measures: detection delay and false alarm rate.

A series of statistical tests for continuous time processes (such as the Sequential Probability Ratio Test - SPRT and the Cumulative Sum - CUSUM test) exist which can be combined with state space recursive algorithms such as the Kalman filter or adaptive filtering techniques for change detection and state estimation of the fire evolution (Gustaffson, 2008). These tests are fully performed at the Remote Fusion/Decision Central Nodes as well as at the Common Operational end user's site of the proposed architecture. It is well beyond the scope of this paper to further analyze this class of algorithms and techniques and how they are integrated and implemented in fire detection software applications. Nevertheless any early fire warning and monitoring system should consider carefully the above design and software component issues, see (ESA, 2008; Tartakovsky & Veeravali, 2004).

Finally it is stressed that in the current literature, assumptions include discrete samples (binary messages) and synchronous communications between the fusion center and the sensor devices. The approaches concerning continuous time processes require additional sampling/ quantization policies. For example fire and flame flickering is time varying and can be modeled as a continuous random process (Markov based modeling approach). In these cases and due to power and transmission constraints the Remote F/D Central Node receives *data in a sequential fashion* and the goal is to quickly detect a change in the process as soon as possible with a low false alarm rate. On the other hand bandwidth limitations require *efficient sampling and quantization strategies* since canonical or regular sampling may no longer be optimum.

5. Integration with First Responders Communication Systems.

It is important in this subsection to take a step further and raise the complex issue concerning First Responders (FRs) needs with respect to communications interoperability extending the scope of the proposed fire detection/surveillance system. This aspect which in our opinion is not usually addressed in various proposed detection/surveillance systems is highly important and operationally critical to any designer who needs to consider a fully realistic high level integrated architecture. In the case of large fire disaster and crisis outbreaks it is highly probable that first responders teams from other European nations and various local emergency response entities will be involved in the crisis monitoring and mitigation efforts. Thus serious interoperability problems of the dedicated heterogeneous communications subsystems will arise due to different communication standards. Indeed at the technological level the variability of available technologies that are used among First Responders networks result in a diversity of characteristics such as signal waveforms, data throughput, latency and reliability, and security (i.e. different cryptographic standards). This situation results in serious compromise of coordination and operational efficiency among FRs even at the monitoring level of the events. Moreover it is well known that at a European and national level different Public Safety authorities have adopted

different systems, equipments and often dedicated technology resulting in a multitude of networks which are non-interoperable. Thus interoperability is in fact a critical factor for European Public – Safety and Security teams that deal with an environment that is complex, interconnected and highly interdependent. We only mention dedicated networks such as Professional Mobile Radios and TETRA/TETRAPOL networks. These networks function under different architectures and air interfaces and so internetworking (roaming capability) is extremely difficult. Additionally new technical capabilities are continuously being adapted by FRs such as ad-hoc mesh broadband networks which are able to provide and extend connectivity over the affected areas of interest and to deliver high data throughput which can be higher than 5Mbs. In Figure 4 a simplified schematic is provided of different FRs with the associated isolated networks.

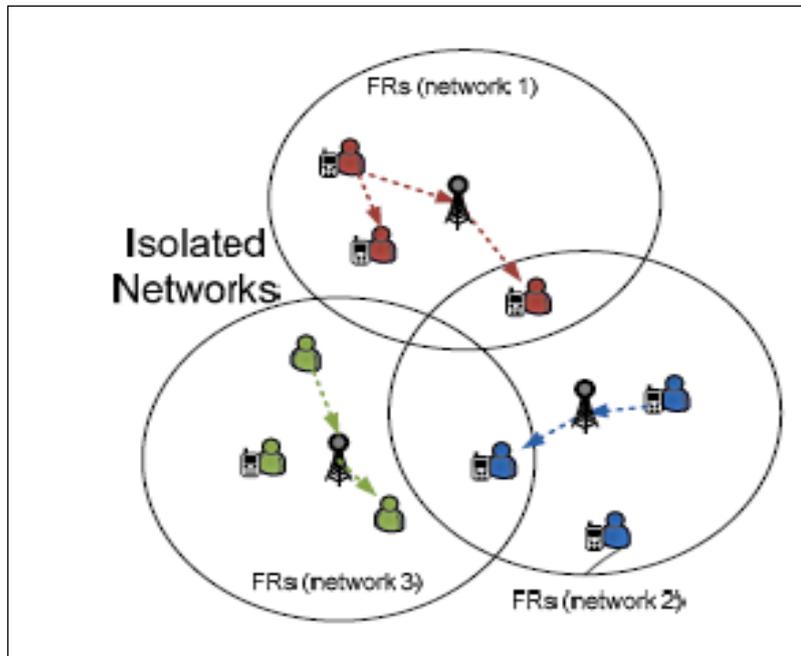


Fig. 4. First Responder isolated communication networks

TETRA has been transformed from circuit switched to IP packet switched architecture (IP protocols) for more efficient integration with other existing technologies. An open design implementation problem then is to account for short term like solutions that will be able to interconnect most existing communication sub-systems and networks using a possible dedicated node ensuring interoperability of all systems without the need to modify existing equipment such as handset devices and other communication infrastructures. In that manner FRs will be able to continue to use current receiver equipment, communication base stations and other critical infrastructures. Thus a specialized gateway could be a possible unifying and cost effective alternative for technical interoperability between different FRs networks capable of supporting cross network - services (**cross-network services**) such as : Voice-calls between TETRA, TetraPol and WiMAX broadband networks, exchange of location based data, exchange of images or seamless transmission of emergency broadcast signals over heterogeneous networks to the specific geographical area of interest or the exchange of a high-priority information across networks. Another issue to be addressed during the design phase is security adopted to critical situations. There are well established techniques and methods (e.g., RSA, DES/3DES, AES encryption) that guarantee security across networking. Nevertheless these type of measures can become a serious problem during a major Fire event since security policies may prohibit communication across different FRs networks. In the same context we mention the existing technical problems related to interoperability even when the same technology is used within a country such as communication between TETRA – TETRA systems.

For the case of Greece TETRA is the dominant technology used by emergency and surveillance authorities. This is also the case for most European countries. In particular TETRA is replacing legacy-PMR technologies, to become the most common technology to use or it is being considered for future adoption where an emerging associated challenge is the additional spectrum requirements for all TETRA future networks as well as Inter-System-Interface (ISI cross border communications). We briefly mention some basic TETRA key-services such as: Registration, Authentication, Individual Half duplex Call, Priority Call, Preemptive Call (emergency), Broadcast Call, Instant Messaging. Also other early – adopters are already experimenting with the use of broadband technologies such as WiMAX or extension of current PSC coverage. In addition as is the case of the proposed Fire Detection Operational System the exploitation of Satellites for

backbone communications infrastructure is especially critical since it provides seamless connectivity between the critical geographical area of interest and the Common Operational Center. This type of space based links is used by the majority of FRs of most European member countries while cellular technology is used as a complementary means. For the hybrid model the S-band satellite services could be used for integration and connectivity so dual use of TETRA/S-band terminals can be exploited providing data rates up to 10Mbps, or a dual mode S-band/L-band terminal providing data rates up to 500Mbps.

In conclusion when designing the architecture of an operational fire detection and monitoring system technical aspects related to the integration with existing FRs communication systems must be addressed and cannot be ignored even at a conceptual level. These include: Interoperability of different networks based on standard protocols (TETRA, TETRAPOL, PMR and WiMAX) or between networks of the same technology (TETRA - TETRA). Interconnection of various full-duplex/semi-duplex networks (such as GSM, ISDN e.t.c.), Air-Interface aspects of each different network technology such as the existing base stations or radio terminals, Network management functions of decentralized networks, connectivity and full integration with satellite systems.

6. Integration of Operational Observation Platforms.

In this subsection we propose specific state of the art sub-systems that can be integrated in the proposed model, as they have reached such a maturity level that may rank them between the operational tools in the emergency response. These components mainly constitute more advanced earth observation and space based subsystems and assets such as ESA's Earth Observation program and ESA's and EC Global Monitoring for Environment and Security program, the so-called GMES program, with its component supporting risk management and emergency response (ESA 2008, 2009; NOAA, 2007). We mention here space and airborne-based surveillance tools and more specifically early warning and near real time monitoring systems with integrated fire risk and fire mapping modeling capabilities using:

- a) Medium to Low-Resolution Remote Sensing sensors.
- b) High-Very High Spatial Resolution Remote Sensing for detailed mapping and damage assessment, and identification of critical infrastructures prone to fire risk.
- c) Airborne thermal sensing platforms.

Several studies show that despite the low spatial resolution of the order of a few kilometers, the SEVIRI instrument onboard the MSG satellites, offer high potential for real time monitoring and disaster management. According to (Roberts et al., 2004) there is a considerable correlation between the fire radiative energy and the corresponding signals captured by the SEVIRI and MODIS sensors. Due to this (Umamaheshwaran et al., 2007) and (Van den Bergh & Frost, 2005) exploited the high update rate of the MSG/SEVIRI images and showed that the use of image mining methods improves significantly the information extraction from MSG/SEVIRI in view to detect fires and model the fire evolution.

With the occurrence of the disastrous wildfires of summers in 2007 and 2009 in Greece, the Institute for Space Applications and Remote Sensing of the National Observatory of Athens (ISARS/NOA) deployed its MSG/SEVIRI fire monitoring service, in complement to the existing operational emergency response state capabilities, providing support to decision makers during the fire fighting operations. Today the MSG/SEVIRI fire monitoring service of ISARS/NOA is offered on a 5-15 minutes basis supporting the actions of a number of institutional civil protection bodies and fire disaster managers all over Greece. With this service the rapid identification of new fires arises has become possible within an average alert time of 5 - 20 minutes. However, there are limitations relating to the instrument's low spatial resolution and geo-location accuracy; due to its distant geostationary orbit (i.e., 36 000 km) and the renown resolution limitations of thermal sensors, the MSG/SEVIRI has a ground sampling distance of the order of 4 km over Greece, which, theoretically, allows for the detection of wildfires with a minimum detectable size of about 0.22 - 0.30 ha see (Prins et al., 2001). Nonetheless, the elevated saturation temperature (>335 K) in the SWIR band minimizes the saturation effect allowing for a sub-pixel fire characterization. This means that, due to the important temperature contrast between the hot spots and the background, outbursts sizing much smaller than the nominal resolution of the sensor may also be detectable under certain conditions as it was the case in all deployed fire monitoring operations in Greece. However, if we want to meet the existing early warning and timely fire detection needs, these figures may not comply with standard detection requirements of fires, the later being approximately 2-3 times smaller, namely 0.1 ha see (Rauste et al., 1999). For this, although the MSG/SEVIRI data are, for the time being, the only satellite data that can be used to improve the reliability in fire announcements, because of their low spatial resolution, they cannot be used alone but as a network component, the later integrating a variety of other sensors as proposed in this paper. It is obvious however that a space based monitoring component as the one of ISARS/NOA, may affect significantly the sensor network topology and lead to high simplifications, especially when the network needs to be deployed in large geographic areas with much accentuated topographic relief as in Greece.

Referring to space based monitoring capabilities it should be noted however that much higher spatial resolution representations can be offered from a number of polar orbit satellite systems like SPOT, LANDSAT, IRS, IKONOS, FORMOSAT-2, etc. However, the main difficulty with these systems is the fixed orbit geometry of the satellite platforms, which results in restraints in revisiting capability both in tactical operations, and in surveillance of vulnerable areas

prone to high risk. In contrast, aircraft (manned or unmanned) are much more easily maneuverable and may very quickly revisit the critical areas providing rapid response for emergency situations. Airborne TIR sensors are usually FLIR (Forward Looking InfaRed) cameras, capable to detect new hot spots that develop rapidly into wildlands. Besides aircrafts equipped with FLIR sensors can be used for supporting fire-fighters in safety tasks, and for detecting escape routes or security zones, in areas where the human visibility is restricted due to the smoke.

For this purpose ISARS/NOA developed and is capable to deploy on demand an airborne fire sensing service under the name SITHON see (Kontoes et al., 2009a). In reality it makes one component of a larger network of sensors, as the whole SITHON system comprises a wireless network of in-situ optical cameras, coupled with the airborne fire detection platform of NOA/ISARS. This network is linked to an integrated GIS environment in order to facilitate real time image representation of detected fires on detailed background maps, that incorporate qualitative and quantitative information needed to estimate the prone to the risk areas and help the disaster management operations (e.g. fuel matter, road network, morphology, endangered locations, endangered critical infrastructures like fuel stations, flammable materials, industrial areas, etc). Moreover, the platform of SITHON includes a Crisis Operating Centre, which receives information in the form of images and data from the wireless sensor detection systems, displays it on wide screen monitors and analyses it to derive the dynamic picture of fire evolution. The airborne system is designed to ensure automatic fire detection. It is mountable on any airborne platform and can be operated within 15 to 20 minutes after the first fire announcement. Once on the platform, SITHON is supported by a fully automated control system, which manages the frame acquisition, the radiometric image calibration and signal thresholding, as well as the dynamic fire detection and geo-positioning within 50-100 m error using on board GPS and INS technology and with the lack of any operating GPS station on the ground. The minimum fire size detectable by the system can be of 3x3 meters on the ground from 2000m Above Sea Level (ASL). The integration of the NOA/ISARS airborne monitoring component in the proposed network topology as indicated in figure 1, enhances the monitoring capacity of the sensor network and improves the automatic fire detection and terrain surveillance capability in geographically extended areas. In the following Figure 4, we provide the SITHON platform. A 310Q CESSNA two-engine aircraft.



Fig. 5. SITHON / Platform – airborne imaging system. (Reproduced picture from (Kontoes et al., 2009a))

7. Future Research Directions

Future research directions could definitely include the integration with ESA's Data Dissemination System DDS, the other polar orbiting systems such as EnviSat and GMES Sentinel spacecrafts, the integration of UAV sensors, which can provide real time data transmission to the ground, and the improvement of algorithms and models used for raw data processing, and data fusion and analysis of space, aerial, and terrestrial observations, to obtain higher detection accuracy and timely announcements of fire alarms. Moreover new fire detection algorithms need to be explored and validated accounting for the local specificities, morphological features and land use/land cover conditions of the area they apply. To this end NOA/ISARS has proposed improvements in the algorithmic approaches proposed by EUMETSAT for fire detection using Meteosat Second Generation satellites, and introduced appropriate adaptations over Greece to avoid fire model detection uncertainties and reduce the returned false fire alarms, see (Sifakis et al., 2009).

At this point, it is briefly mentioned that our proposed model could further be extended and integrated with the web based European Forest Fire Information System consisting of two operational sub-modules: The European Forest Fire Risk Forecasting System (EFFRFS) which is a module for fire risk forecasting information and processing and the European Forest Fire Damage Assessment System (EFFDAS), which is capable of evaluating and assess the damage caused after a fire event using satellite imagery.

Furthermore, two additional elements could be certainly proposed for integration in the proposed architecture for future deployments: Unmanned Aerial Vehicles (UAV's) for surveillance and monitoring tasks especially for large-scale fire events and ESA's new initiative of a Satellite Based Alarm System. The latter case needs further intensive technical

efforts (such as the identification of appropriate frequency selection and interoperability aspects) taking advantage of the current GSM/UMTS systems for broadcasting messages to mobile phone users in dedicated geographical regions where the fire event is taking place. UAV sensors capable of carrying IR and video cameras and instrumentation with high-resolution capabilities for dedicated fire and hot spot detection, as the airborne SITHON observing system presented above, it seems very promising for reliable and fire monitoring services see (ESA, 2008; Kontoes et al. 2009a; 2009b; 2009c). More explicitly they can serve concurrently several tasks such as vegetation mapping and forestry, fire fighting and emergency management airborne communication collection and relay, as well as environmental monitoring before and after the fire event. With such systems further localization and confirmation of fire sources in conjunction with the proposed fire detection system, can be achieved therefore minimizing significantly the false alarm rate. We mention that this type of systems and their integration with existing space and terrestrial infrastructures are currently under ESA's research efforts. Indeed co-operative Satellite -UAS missions can deliver unrivalled global area coverage and time-critical, very close range operational capabilities (ESA, 2008; 2009). Even more in the near future the European Data Relay Satellite System (EDRS) will be a reality and further integration with the above components will be an attractive space based sustainable solution. The EDRS system offers (and will be technically capable in offering) real-time or nearly-real time response times for rapid information updating and Rapid Mapping activities and Surveillance including the "very urgent" imaging data downlink as well as meeting the growing demand for "<1 meter" resolution data availability (ESA, 2008).

Finally we should mention that in the case of Greece, several initiatives namely RISK-EOS, SAFER and LinkER - are run by the National Observatory of Athens - Institute for Space Applications and Remote Sensing, funded by the European Space Agency and European Union within the GMES program framework (Kontoes et al., 2009b; Robertson et al., 2004). These initiatives foresee the provision of additional services that respond but not limited to, wild fire crisis management in the entirety of Greece. In particular the central and basic set of core services provided during the crisis are near real time fire mapping (the so called rapid mapping) at high and very high spatial resolution, as well as continuous monitoring and early warning on a 15 minutes basis using medium to low spatial resolution satellite derived products. These services are offered through dedicated gateways of GMES, making appropriate use of properly developed interfaces linking the local End User community and the corresponding GMES National Focal Point, that is the National Observatory of Athens with the Emergency Response Core Services (ERSC) gateway.. The main aim is to rapidly assess and disseminate information on fire occurrence and combine it with additional in-situ and space/aerial collected data to effectively support early warning, as well as decision-making and coordination of the emergency response actions during fire fighting. The integration of these newly developed operational geo-information services in the framework of GMES, to the proposed architecture is an innovative element providing complementary fire detection and fire mapping information that needs to be considered for future directions, in the implementation of more reliable and integrated fire warning and monitoring architectures. In fact a large-scale deployment of the proposed system in various geographical areas of Greece could be well complemented by the integration of additional fire occurrence and fire spreading evidences through NOA's established monitoring capabilities and GMES/ERCS gateway (Kontoes et al., 2009c).

8. Conclusion

In this paper the basic model architecture for timely and accurate fire detection and surveillance according to operational user requirements is described. Hardware and software issues as well as satellite, airborne and terrestrial data handling technologies have been described and their integration to the proposed network observing architecture is justified. Some important and mission critical communication issues related to First Responders Network interoperability were also provided. These issues are of high priority when it comes to further integrate and extend the proposed system with the response emergency authorities on a national and international level. Additionally the integration of Earth Observation platforms is commented and their integration was presented. Moreover some important theoretical aspects of decentralized detection strategies were provided.

Time is the most crucial parameter in fire combating and fire containment. The level of efficiency depends on the promptness of the detection system to receive and send in almost real time its alarming signals indicating fire outbreaks and fire locations. The state-of-the-art in most of the deployed fire sensor systems, seem not to take this into account, namely various aspects related to sequential change detection design parameters and optimality issues arising in decentralized detection schemes over wireless communication channels, as proposed in this paper. On the other hand part of the existing literature regarding distributed detection systems is strongly theoretical and involves esoteric and often deep results from the fields of statistical estimation and sequential change detection theory.

This article concludes to an operational and realistic, in terms of efficiency and cost of deployment, initial modeling solution, and ensures that the proposed model is easily expanded to the newly developed and emerging Earth Observation, Telecom, Navigation, Aviation and Advanced Sensor technological advancements, in order to efficiently address the problem of early detection and prompt emergency response in the case of fire disasters. The disaster management community will be soon facing a great technological peak, enabled by the advancements in aviation, sensor and imaging technologies, telemetry, data fusion and processing, and geo-information/value added products use. The

authors are currently involved in assisting the integration of these technologies to the daily practice of the disaster management community through on-going research and development in the domain of state-of-the-art integrated application systems.

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