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Preventing forest fires using a wireless sensor network

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Abstract: Forest fire is a natural phenomenon in many ecosystems across the world. The forecasting of fire danger conditions resembles one of the most important parts in forest fire management. A ZigBee-based wireless sensor network was proposed for monitoring fire danger and predicting the behaviour of fire after occurrence. This technique is intended for real-time operation, given the urgent need for forest protection against fires. The architecture of a wireless sensor network for forest fire detection is described. From the information collected by the system, decisions on firefighting or fire prevention can be made more quickly by the relevant government departments. We believe that by making the sensor network able to reconfigure rapidly in response to changes in the local conditions upon which the network is dependent, we will generate an adaptable weather monitoring and fire detection system.

Keywords: wireless sensor network; hardware circuitry; protection engineering: fire management; ZigBee

Forests are part of the important and indispensable resources for human survival and social development that protect the balance of the earth ecology (The State of Food and Agriculture 2007). This study aims at critically analyzing the current operational forest fire danger forecasting systems and their limitations as well as synergy between operational forecasting systems and remote sensing-based methods. The latter has been investigated in the past but the results are complex in nature. In general, the operational systems use point-based measurements of meteorological variables and generate danger maps upon employing interpolation techniques. Theoretically, remote sensing data may be used to overcome the uncertainty associated with the interpolation techniques. Although considerable efforts were given to develop fire danger monitoring and forecasting systems, most of the monitoring systems are focused on determining the danger during and/or after the period of image acquisition. Thus, the elaborate understanding of these undertakings would be worthwhile to advance research in the area of fire danger in the context of making them operational. Forest fires are among the most serious disasters to forest resources and the human environment. As their frequency increases due to climate changes and other factors, the prevention and monitoring of forest fires become a global concern.

The aim of this study is to make use of the existing information technologies and generate an approach towards forest fire monitoring, detection and warning. Seeking an opportunity to make a network of fire management units more accessible to developing countries will contribute to combating deforestation.

A closer look at the state-of-the-art will reveal many approaches to fire monitoring and warn-

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ing within forests. Currently, forest-fire prevention methods largely consist of observation from watchtowers and satellite monitoring (Murray 2016). Although observation from watchtowers is easy and feasible, it has several weak points. Firstly, this method requires many financial and material resources and a trained labour force. Such a demand runs counter to our goal: an expensive system will serve no solution to the problem of global forest protection. Secondly, there is a human factor, meaning carelessness, absence from the post, inability for real-time monitoring and the limited area coverage. The satellite systems are often referred to as an alternative but they do not fully meet the purpose of this study either. The satellite detection systems have a restricted scope of application (e.g., long scanning, low resolution, loss of image quality during cloudiness, etc.) (Sá et al. 2017; Javadnejad et al. 2019).

A wireless sensor system designed for the application in forest environment is a new but not unique proposal for a number of authors who offered a similar system but with a different architecture. Therefore, this study chose and developed a conceptually close to the research objective technique from the set of forest monitoring approaches that involved a wireless network. Hence, Khamukhin et al. proposed an approach which is based on the classification of acoustic signatures of the forest fire. They suggest comparing the recorded acoustic emission spectrum with a set of spectra samples from the typical fire emissions in a database (Khamukhin et al. 2017). This method implies the collection of acoustic data using the wireless sensor network and subsequential analysis of thereof in the central processing node. In their earlier work (Khamukhin, Bertoldo 2016), the authors proposed an approach to investigating acoustic emission upon the fire outbreak, which is clearly worth exploring.

Abdullah et al. developed an approach which is comparable to ours, based on the ZigBee protocol, with a broad range of sensors and detectors applied, from sensors reading meteorological variables (e.g., temperature, humidity, and pressure), to oxygen, carbon dioxide and carbon monoxide detectors (Abdullah et al. 2017).

Saldamli et al. offered a network comprising wireless smoke and gas sensors that were connected with each other in the Internet of Things (Saldamli et al. 2019). There are numerous works with a similar approach that is placing sensors on the ground and we have chosen only the closest analogues for our work. Differences can be found in data being gathered and hardware but sensors are invariably located within the protected area and connected in a wireless network.

Thus, multiple methods for forest fire detection can be broken down in two groups:

(*i*) visible and/or infrared image processing and automatic detection of smoke and heat from fire by stationary cameras installed on watchtowers or by mobile cameras installed on any aircraft (airship, drone, balloon, satellite);

(*ii*) monitoring of meteorological variables such as temperature, humidity, smoke, etc. using sensors located within the forest, and transmission of data to the tracking station via the network.

We suggest placing a carbon monoxide detector onto the sensor platform, as carbon monoxide is a definitive marker of intense combustion process and easily detected by relatively simple sensors (Vetter et al. 2015; Yang et al. 2015). The important part here is that since this study aims to offer a simplified affordable sensor and a sensor-based system for developing countries, the concentration of carbon monoxide on the detector can be regarded as sufficient and consistent with the current objectives. Compared with the normal meteorological information and basic forest resource data, the system can make a quick assessment of a potential fire danger. Before the source of combustion becomes visible via satellite, the traces of carbon monoxide will signal the occurrence of combustion. Together with meteorological data (temperature and humidity), carbon monoxide detection allows judging the increase in fire danger and predicting the speed and direction of its spread. For interpretation reasons, this approach provides information about the fire status that is sufficiently complete. Further expansion of the sensor range can be considered impractical and redundant. The analysis of carbon monoxide concentration, humidity, wind speed and direction enables a forecast of fire hazards. For processing to be adequate, the network sends these data to the relevant department.

Substantiation of the sensor system configuration may be found further in the text. There are three factors whose combined effect contributes to the ignition of a forest fire: the fire source, environmental elements and combustible material (Zhang et al. 2015; Ye et al. 2017). According to the Fire

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Weather Index Forecast, the moisture content of the combustible material plays an important role in forest fires. As the dead forest fuel and the air are exchanging moisture on a constant basis, the relative humidity is crucial. Hence, low humidity takes moisture from the fuels, while fuels in turn take moisture from the air when the humidity is high. Light fuels (e.g., grass and pine needles) gain and lose moisture quickly with changes in the relative humidity. For example, when the relative humidity drops, these fuels become drier and thus increase the fire behaviour. Heavy fuels, by contrast, respond more slowly to these changes. To see significant changes in the heavy fuel moisture, there must be significant moisture, usually from more than one storm (Chowdhury, Hassan 2015; Wang et al. 2017). Therefore, the moisture content of combustible materials is a major point of assessment and predicts whether a fire will take place and how quick it will spread if eventually occurs. Relative humidity in this regard is an integral weather indicator because it takes into account the absolute humidity of the locality together with variables like temperature and the speed of wind (Coen, Schroeder 2017; Abdollahi et al. 2018). Water evaporation can be directly affected by relative humidity. At the same time, the physical properties of combustible materials can be changed indirectly by the air temperature. Thus, relative humidity and air temperature are regarded as the two main factors that affect the moisture content of the fuel. Certainly, we can draw our attention to more complex models but for creating a wireless network for wide-ranging operation in distant forests, a small number of crucial factors must be involved in the measurement. A carbon monoxide detector signals about the fire that has been spreading by the time it was detected, while sensors that measure relative humidity, temperature, the level of carbon monoxide, and the wind strength collect data for assessing the risk of fire occurrence.

MATERIAL AND METHODS

This network is composed of numerous and ubiquitous microsensor nodes which have the ability to communicate and calculate. These nodes can monitor, sense and gather information about different environments and various monitoring objects cooperatively. ZigBee is a low-rate, low-cost and low-power kind of short-range wireless network communication protocol. ZigBee is an NWK- or APS-layer specification built upon the PHY and MAC specifications of IEEE 802.15.4. ZigBee and IEEE 802.15.4 define the operation of the Wireless Personal Area Networks (WPAN). ZigBee is targeted for battery-powered applications that require secure data transfer and low data transfer rates. With low power consumption, ZigBee supports peer-to-peer, tree, star, and even mesh topology, allowing for message relaying and routing. In addition, ZigBee specification also contains the ability to select a routing algorithm (depending on the application requirements and network status) and a mechanism of standardization (i.e., application profiles, cluster library, endpoints, bindings, flexible security mechanism) and ensures the ease of deployment, maintenance and upgrade. Compared with other wireless technologies, ZigBee has unique advantages of safe and reliable data transmission, an easy and flexible network configuration, low equipment costs, and low power consumption. By applying a wireless sensor network based on ZigBee to a forest fire monitoring system, information about temperature and humidity could easily be collected in any part of the forest and processed at any time. In addition, the system can be extended significantly, the cost of equipment maintenance could be reduced, and the whole system could be optimized.

Forest fire monitoring system based on a ZigBee wireless sensor network. A ZigBee wireless sensor network system includes sensor nodes, gateways (routers) and a monitoring host computer. To decrease the loss of energy and data packets, a cluster tree network topology structure is applied in this design (Jameii et al. 2015). Sensor nodes fitted with microprocessors of low processing capacity are distributed randomly in the forest and nearby areas to collect fire monitoring parameters such as relative humidity and atmospheric temperature (Sudha et al. 2018). Depending on the part the different sensor nodes play in the whole network, they are divided into three categories: ordinary bottom nodes, cluster heads and network coordinators. Data collected is transmitted to its own cluster head by an ordinary bottom node. A cluster head mainly handles data fusion and data packet transmission. Via the cluster head, data collected by ordinary bottom nodes in the cluster can be fused and transmitted to the nearest network coordinator and

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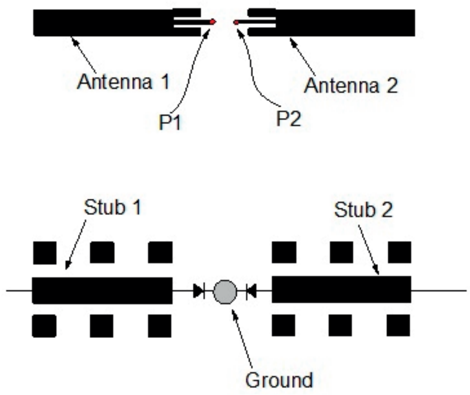

Figure 1. The microstrip antenna circuit, front and rear views

data packets transmitted by the network coordinator can be broadcast to related clusters. A network coordinator mainly deals with basic network management functions such as network configuration, equipment registration and access control. Data information can be transmitted to routers by wireless communication. When receiving data, routers establish a local database and then transmit data to the monitoring host computer via internet, which provides a decision-making basis for forestry or fire prevention departments. The power module supplies power to the other three modules and drives the nodes, making it the key factor for the effective operation of the network (Kumar 2017).

Antenna. The intriguing part of our approach is implemented via a microstrip antenna, which is attached to the blade of a weather vane. The microstrip antenna consists of two fed monopoles and two parasitic loads. The nature and value of the load are obtained using the Uzkov equations (Dihissou et al. 2017), allowing for the calculation of current weighting coefficients in the case of two separately fed antennas, in order to maximize the gain and directivity in a given direction. Recongurability is achieved using rector and director elements activated by PIN diodes to reduce the back radiation and pointing in the desired direction. Thus, the first system is obtained which consists of two elements, one fed and the other loaded with an inductor, with a maximum gain of 5.2 dBi in simulation and 4.7 dBi measured at 2.4 GHz in azimuthal directions of 90 and 270 degrees.

The microstrip antenna circuit is shown in Figure 1, while Figure 2 demonstrates its calculated radiation pattern.

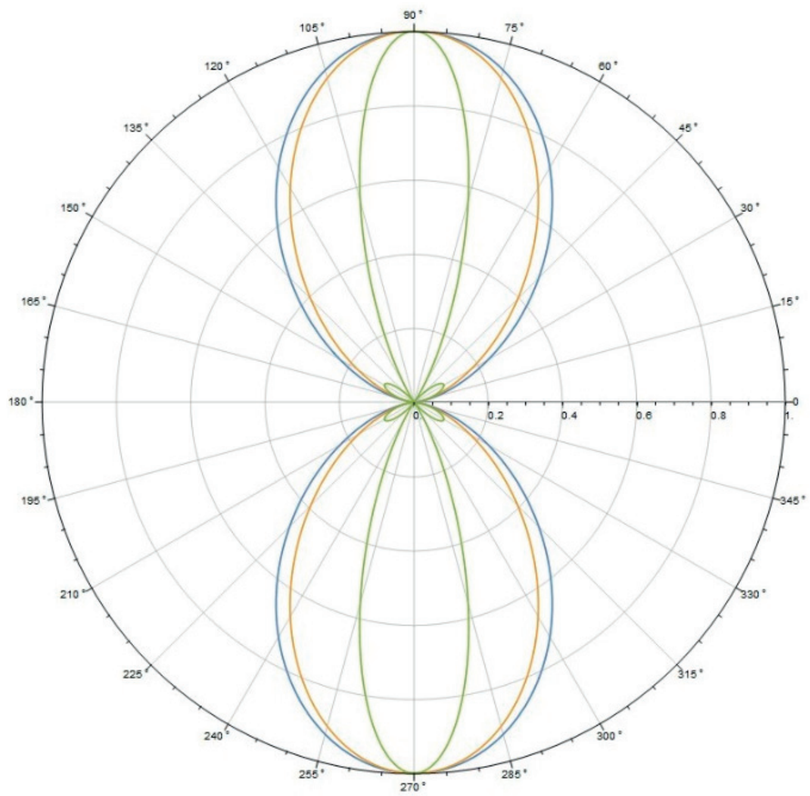

Figure 2. Radiation pattern of a microstrip antenna with narrow petals resembling higher frequencies (petal frequencies: blue (868.6 MHz, the widest one); brown (928 MHz); green (2 483.5 MHz, the narrowest one))

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Figure 3. A photographic view of a weather vane

With radiation patterns stretching from all nodes of the system, the coverage area of the wireless network will obviously become highly dependent upon weather conditions and will generate lines along the direction of the air. High directivity of the antenna allows positioning of the network elements over long distances. Certainly, this will inhibit the circular communication between nodes but attaching a microstrip antenna to the weather vane will allow the communication within network along the wind direction. In the event of fire, the combustion products will spread via wind and here is when the ZigBee-based wireless sensors go into action or reconfigure themselves. Sensors located in the way of a fire front self-organize in a locally structured network to provide high optimization of fire danger data processing along the wind corridor. Thus, the network will gather and analyze information before the fire front gets closer, directly in the fire area and, if the equipment bears the short-term heat, in the post-fire areas. Heuristically, such an ability of the wireless network to situationally 'refocus' without external algorithms seems to be the most appropriate feature when it comes to the forecasting of the forest fire behaviour. With this ability, the wireless sensor network becomes adaptable and achieves the basic level of artificial intelligence (Figure 3).

System hardware design: any DS2401 chip, produced by the Dallas Company, has a different sequence code. Except for the grand pin, the DS2401 chip has only one function pin which can supply power and deal with input and output. The power supply for the system is provided by moderate-capacity photovoltaic batteries. To assure a stable working state and maintain working characteristics, a MAX1724EZK30 is used in the nodes to keep the working voltage steady. A microstrip antenna, shown in Figure 1, is applied in the system. The antenna is 5 cm long, weighs 20 g and is easy to install. Its typical emission frequency is 2.4 GHz. 4.2

The hardware configuration of the gateway includes the main processor, a memory unit, an RF receiver and transmission module, a GPRS communication module, and I/O, Ethernet and extension interfaces. In the RF receiver module, a CC2430 is used, through which bi-directional communications with sensor nodes are achieved, data from nodes can be received and control orders can be sent to nodes. To deliver data transmission inside the ZigBee network in this design, a system of active requests for information by the monitoring host computer and passive responses by the sensor nodes is used. Figure 4 shows the data transmission process.

DISCUSSION

Fire danger conditions are the most important part in the integrated fire management (Watts, Hall 2016) due to their broad applicability (e.g., prescribed burning area identification, reduction of intensive survey operations, quick detection of fire events and deployment of firefighting units, etc.). Hence, our work falls within the mainstream of problem development. The last several decades have seen a deep investigation of remote sensing-based techniques for application in fire danger management (Murray 2016). These methods can be broken down in two major groups: fire danger monitoring systems and fire danger forecasting systems. Our work tackles these two approaches in combination. In particular, to monitor fire danger conditions, some environmental variables are derived from optical, thermal and radar images (Chowdhury, Hassan 2015), while our approach gathers data from a network of sensors located on the ground. Moreover, since the fire danger conditions define the likelihood of fire occurrence, the above methods may not give the necessary result, as they capture dangerous conditions during fire and/or after the fire starts. However, data gathered by our approach will be available at a daily temporal scale which is fully operational and used by fire managers for fire behaviour and suppression strategies. The remote sensing-based methods used to forecast fire danger conditions will thus fail to keep

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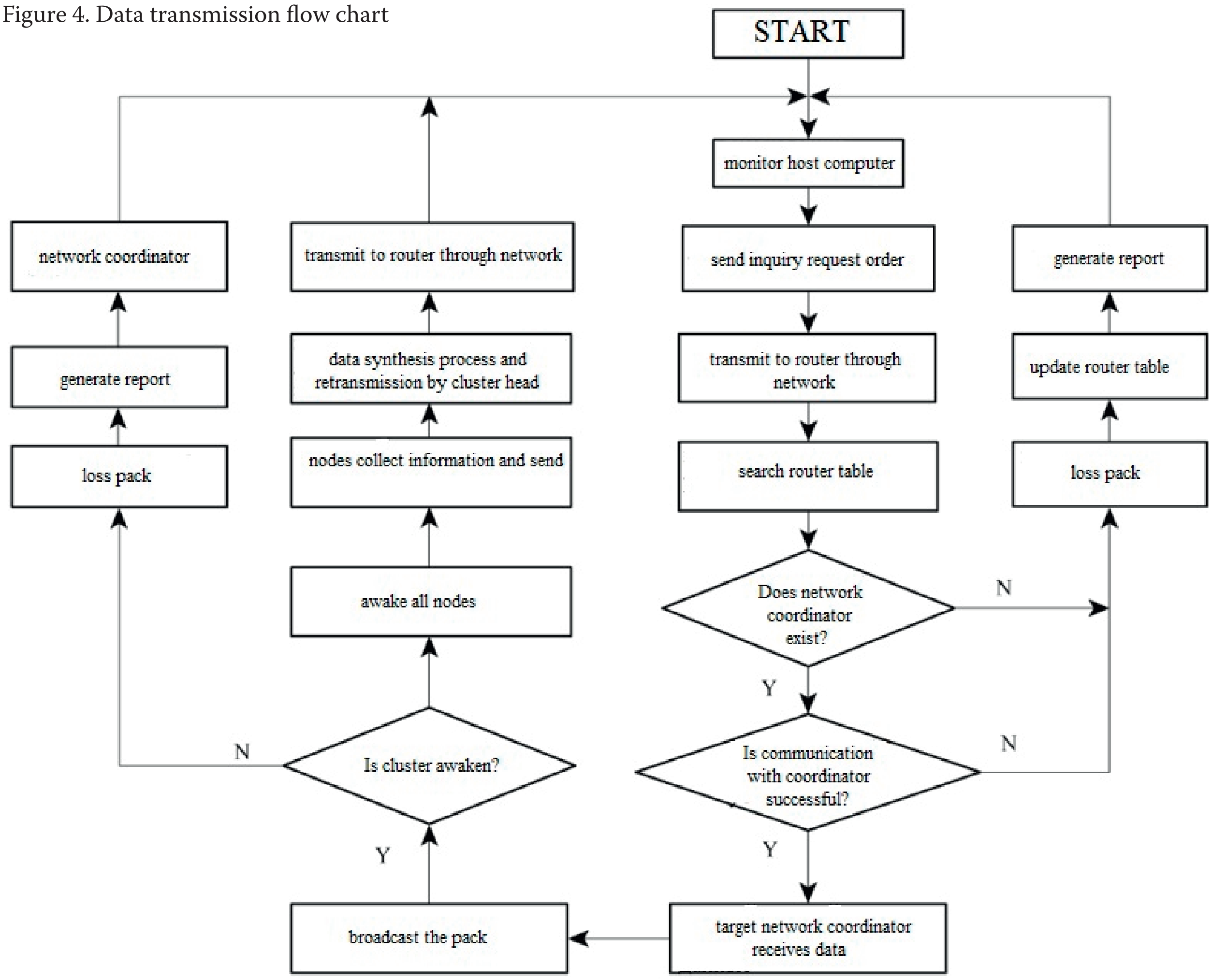
Figure 4. Data transmission flow chart



with the run of events, while our approach will provide the relevant firefighting units with the most relevant information. Most of the fire danger forecasting systems have a moderate range and coarse spatial resolution. The on-site data-measuring system is obviously more efficient.

Comparing our approach with the closest analogues, we can note several interesting projects. For example, Abdullah et al. developed an approach which is comparable with that proposed here. However, we find oxygen and carbon dioxide readers in their system redundant and incapable of directly detecting when a fire starts (Abdullah et al. 2017). A pressure sensor may be considered useful in weather characterization but since the atmospheric pressure is a volumetric quantity, there is no need to measure it from hundred different places, taking one measurement is more than enough. However, the approach under discussion refers to two types of hierarchically related devices, and the node heads are equipped with an additional sensor that reads the strength and direction of the wind. We consider the measurement of wind-related variables more important in the forest fire behaviour forecasting. From this perspective, it seems more reasonable to assign this function to general devices. Saldamli et al. offer a network that consists of wireless smoke and gas sensors which are connected in the Internet of Things. Comparing with our work, their approach implies an excessive bandwidth of communication channels, which will result in high cost and, consequently, limited application (Saldamli et al. 2019).

The method proposed by Khamukhin et al. (2017) suggests gathering acoustic data with wireless sensor networks which will be further processed in the central processing node. Their other approach is also worth being improved (Khamukhin, Bertoldo 2016). The advantage of investigating acoustic emission upon the fire outbreak is that acoustic

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waves propagate relatively further, faster and with higher uniformity compared to signals that various gas sensors can detect. However, this strength appears also like a weakness, as a chemical signal propagates more slowly but along the direction of the air mass, that is along the corridor with a high likelihood of fire occurrence. Hence, wireless sensors that measure wind direction and strength provide critical information, which positively distinguishes our work among other research papers.

So far, the approach towards designing a wildfire protection system based on a wireless network is only a proposal but we believe that with distinctive and unique features, it can solve the problem of wildfire with a relatively cheap tool. Such an opportunity can be valuable to developing countries.

CONCLUSION

Wireless sensor networks are increasingly applied in the field of environmental and ecological monitoring. Especially in difficult and harsh environments, they have advantages that traditional monitor systems lack. This study offers and lays groundwork for an adaptive wireless network of reflective sensors that measures meteorological variables on-site while reconfiguring for the effective area coverage. Such sensitivity becomes possible with the use of a bidirectional high-directivity microstrip antenna, attached to the weather vane blades. The use of ZigBee, which permits the low-level network reconfiguration, makes the network configuration dependent on weather conditions without involving the computing power. The reconfiguration algorithm is not dependent upon the number of sensors in the network. Moreover, it does not require higher computing power than a single-chip wireless sensor needs to build an adaptive network in real time. It does not require iterative calculations and therefore cannot be classified as a highly complex algorithm. The focus on a small number of measurements together with the carbon monoxide monitoring suggests that the proposed solution will not be expensive, will be operational in the real-time mode, and efficient.

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