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Welcome from Editor

It is my pleasure to bring to you the compiled papers from the Science Day of the AFAC and Bushfire CRC Annual Conference, held in the Sydney Convention Centre on the 1st of September 2011.

These papers were anonymously referred. I would like to express my gratitude to all the referees who agreed to take on this task diligently. I would also like to extend my gratitude to all those involved in the organising, and conducting of the Science Day.

The range of papers spans many different disciplines, and really reflects the breadth of the work being undertaken, The Science Day ran four steams covering Fire behaviour and weather; Operations; Land Management and Social Science. Not all papers presented are included in these proceedings as some authors opted to not supply full papers.

The full presentations from the Science Day and the posters from the Bushfire CRC are available on the Bushfire CRC website www.bushfirecrc.com.

Richard Thornton

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Micro-scale Forest Fire Weather Index and Sensor Network

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Abstract

Micro-scale fire weather index (FWI) system locates impending bushfires to their exact locations well before their occurrence and remotely alerts the authorities with detailed fire management information. It enables high temporal and spatial resolution of information on bushfire activity. This is considered ideal for early warning system of bushfire-prone regions. A large number of low-cost, intelligent and wireless sensors are deployed within the area of interest with the sensors located at short distances apart. These sensors intimately interact with the physical environment of the bush/forest floor and gather the necessary information which is shared among the neighbouring sensors wirelessly. The information is fed to the hazard prediction algorithm embedded into each sensor unit to generate an alarm for any fire hazard and for data management. The system could be organized to alert the fire management authority timely via the available backbone communication (GSM, Internet or satellite) link.

Keywords: Wireless sensor network, Micro-scale, Bushfire hazard, Fire Weather Index

Introduction

The existing standard Fire Weather Index (FWI) system acquire current weather parameters, elevation and produces the sub-indexes of the FWI system daily at noon local time. The FWI indexes are indicators of daily potential and behaviour of bushfires. The FWI system relies on sparsely distributed meteorological stations as its current weather parameter data sources. Data from the meteorological stations are transferred to a central processing and repository centre via satellite communication. At the central processing and repository centre, weather parameter grids for the entire national area will be produced. Geographic Information Systems (GIS) software is used to interpolate the weather data between stations taking into account elevation data to produce gridded weather maps. The FWI system components are then calculated on a cell-by-cell basis according to the equations in [1] to produce the FWI maps. While the existing FWI system does a great job in producing daily bushfire hazard maps, it lacks several desirable capabilities which are very important from fire management and control point of view.

Limitations of the existing FWI system

In the existing FWI system, weather data grids between stations are obtained by interpolating data from outlying stations. Therefore, the hazard prediction spatial resolution is estimate rather than actual. Consequently, the hazard maps for locations further away from the stations are estimates and potentially of low accuracy. In cases of a station failure, the region around the station is cut-off and the data grids' values between stations will degrade in accuracy. Further, the standard FWI system produces fire hazard ratings on daily (24 hour time resolution) basis and hence is unable to capture fire potential and behaviour fluctuations at higher time resolution, information which enables fire managers to understand and control fire dynamics at higher time resolutions. The system as is does not allow real-time querying of specific forest domain at specific times for hazard rating. This may be necessary when there are specific domains of the forest that require special attention such as urban-rural-interface, national parks, and nuclear facility. A new station start-up and integration also involves high cost, labour and long time.

Micro-scale FWI system is an attempt to implement scaled-down version of the Canadian FWI system for fire danger monitoring of a relatively smaller geographic area. It considers an area as small as few square meters or as large as many square kilometres. It is specifically important for local forest zones where the nature of the vegetation and topography largely differs from the surrounding forest area. It is based on deployment of large number of low-cost, low-power, and small-size weather sensor nodes linked by low-power wireless communication network –Wireless Sensor Network (WSN).

The weather sensor nodes as the basic building blocks of the micro-scale FWI system are capable of individually probing their surroundings and acquiring weather parameters such as temperature, relative humidity, wind speed, and rainfall. They are also capable of minor data processing and short range wireless communication with other nearby nodes.

In order to monitor a specific forest zone using the micro-scale FWI system, the forest zone is divided into grids of small square cells (e.g. 20m x 20m) and a weather sensor node is placed in each cell. Since the size of the square cells can be as small as possible, high spatial resolution weather parameter measurements can be made by taking multiple measurement points in the region. The fire danger rating values' accuracy is robust to a single or a few sensor failures due to the dense measurement points. The size of the forest zone that can be monitored using micro-scale FWI system is determined by the WSN which usually employs numerous low cost nodes communicating over multiple hops to cover a large geographical area.

The micro-scale FWI system also provides high temporal resolution fire danger rating as the system can make low-power frequent measurements and transmit (e.g. hourly) to base station. The system can also operate in event detection mode in which, the individual sensor nodes instantaneously send information to the base station upon detection of predetermined danger rating threshold.

The micro-scale FWI system allows intermittent interaction to the normal (e.g. hourly) operation for querying specific region's situation. Such queries can be generated and injected into the network at the base station.

The data sources and FWI system components are carefully analysed and calculations are transposed to suite relatively smaller area fire danger rating system.

Related work

A wildfire is any uncontrolled fire in combustible vegetation that occurs in the countryside or a wilderness area [2]. Other names such as bush fire, bushfire, forest fire, grass fire, wild land fire may be used to describe the same phenomenon depending on the type of vegetation being burned [3]. Wildfire differs from other fires by its extensive size, the speed at which it can spread out from its original source, its potential to change direction unexpectedly, and its ability to jump gaps such as roads, rivers and fire breaks [4].

Wildfires may be ignited by a number of natural causes such as lightning, volcanic eruption, sparks from rockfalls and spontaneous combustion [5, 6]. However, the most common causes of wildfires varies throughout the world, and includes human sources such as arson, discarded cigarettes, sparks from equipment, and power line arcs [7, 8]. These ignition sources have to be brought into contact with combustible material such as vegetation for the fire to occur. Weather and climatic conditions play major roles in drying the vegetation to ignition point. Hence weather and climatic conditions are the major parameters in wildfire potential and spread modelling.

An adequate fire-intelligence system is the cornerstone for effective management of wild land fire. A major component of any fire-intelligence system is a fire-danger rating system. The purpose of fire-danger rating systems is that where the fire environment (i.e. weather, fuels, and topography) varies in space and time, and where fire-management resources are costly and limited, a means is needed to allocate the available resources across a region or country from day to day or place to place, on the basis of fire danger. The process of systematically evaluating and integrating the individual and combined effects of the factors influencing fire potential is referred to as fire-danger rating. Fire-danger rating systems provide for one or more qualitative and/or numerical indices of ignition potential and probable fire behaviour [9].

One of the most comprehensive forest fire danger rating system in North America is the FWI system developed by the Canadian Forest Service (CFS) [10]. The Canadian FWI System is based on several decades of forestry research [11] and will be used for the purpose of this work.

FWI System

The FWI was originally proposed by Van Wagner [1] for the wildfire prevention in Canadian forests [12]; it is calculated from a set of weather parameters and described the evolution of the current moisture content of different fuel layers of the forest system, together with the influence of wind in fire propagation. It is widely used by many fire prevention systems in the world [13]. The FWI system models the complex relationships between the forest weather variables, the forest floor moisture profiles, and the Fire Behaviour Indices [1,14]. The FWI system consists of six components that account for the effects of different forest weather variables on likelihood and behaviour of forest fires; the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC), the Initial Spread Index (ISI), The Build Up Index (BUI), and the FWI. The general structure of the FWI system with modifications for Micro-scale FWI is shown in figure 1 below.

Fine Fuel Moisture Code (FFMC)

The FFMC model requires the current moisture condition m of the fuel, which is determined by the combined effect of rainfall and absorption/desorption of atmospheric moisture. Given as

$$FFMC = 59.5\frac{250-m}{147.2+m} \quad (1)$$

Duff Moisture Code (DMC)

The duff moisture code (DMC) is a combined effect of rainfall modified duff moisture code DMC_r and evaporation from the duff layer DMC_d which are functions of temperature (T), relative humidity (RH) and effective day length (L_{eff}).

$$DMC = DMC_r + DMC_d \quad (2)$$

where $DMC_r = 244.72 - 43.43\ln(m_r - 20)$ and $DMC_d = 1.894(T+1.1)(100-RH)L_{eff}10^{-4}$.

Drought Code (DC)

The drought code (DC) is determined by estimating the change in a moisture equivalent scale caused by a source term and loss term. Given as:

$$DC = DC_r + DC_d \quad (3)$$

where $DC_r = 400\ln(800/Q_r)$ and $DC_d = 0.5(0.36(T+2.8)+L_f)$,

DC_r is the rainfall modified drought code, Q_r is rain modified moisture equivalent scale. DC_d is moisture loss from duff layer, T is temperature, and L_f is seasonal day length adjustment.

Initial Spread Index (ISI)

The initial spread index (ISI) is related to FFMC and wind speed, v, limited to a maximum of 100 km h^{-1}. It has the wind speed component, FW and the FFMC component, FF, related through the current moisture condition m.

$$ISI = 0.208(FW)(FF) \qquad (4)$$

where $FW = e^{0.5039v}$ and $FF = 91.9e^{-0.1386m}\left(1+\frac{m^{5.31}}{4.93\cdot 10^{7}}\right)$.

Build Up Index (BUI)

The build up index (BUI) is calculated by combining DMC and DC. A form of the harmonic mean of the DMC and the DC is used to calculate the BUI [11], to ensure that changes about smaller values of either the DMC or the DC will receive a greater weight.

$$BUI = \begin{cases} \dfrac{0.8DMC\cdot DC}{DMC+0.4DC} & DMC \le 0.4DC \\ DMC-\left(1-\dfrac{0.8DC}{DMC+0.4DC}\right)\left[0.92+(0.0114DMC)^{1.7}\right] & DMC > 0.4DC \end{cases} \qquad (5)$$

Fire Weather Index (FWI)

The fire weather index (FWI) is a function of both the BUI and the ISI and is given as;

$$FWI = \begin{cases} B & B<1 \\ e^{2.72(0.434\ln B)^{0.647}} & B \ge 1 \end{cases} \qquad (6)$$

Where, $B = 0.1(FD)(ISI)$ and $FD = \begin{cases} 0.626BUI^{0.809}+2 & BUI \le 80 \\ \dfrac{1000}{25+108.64e^{-0.023BUI}} & BUI > 80 \end{cases}$

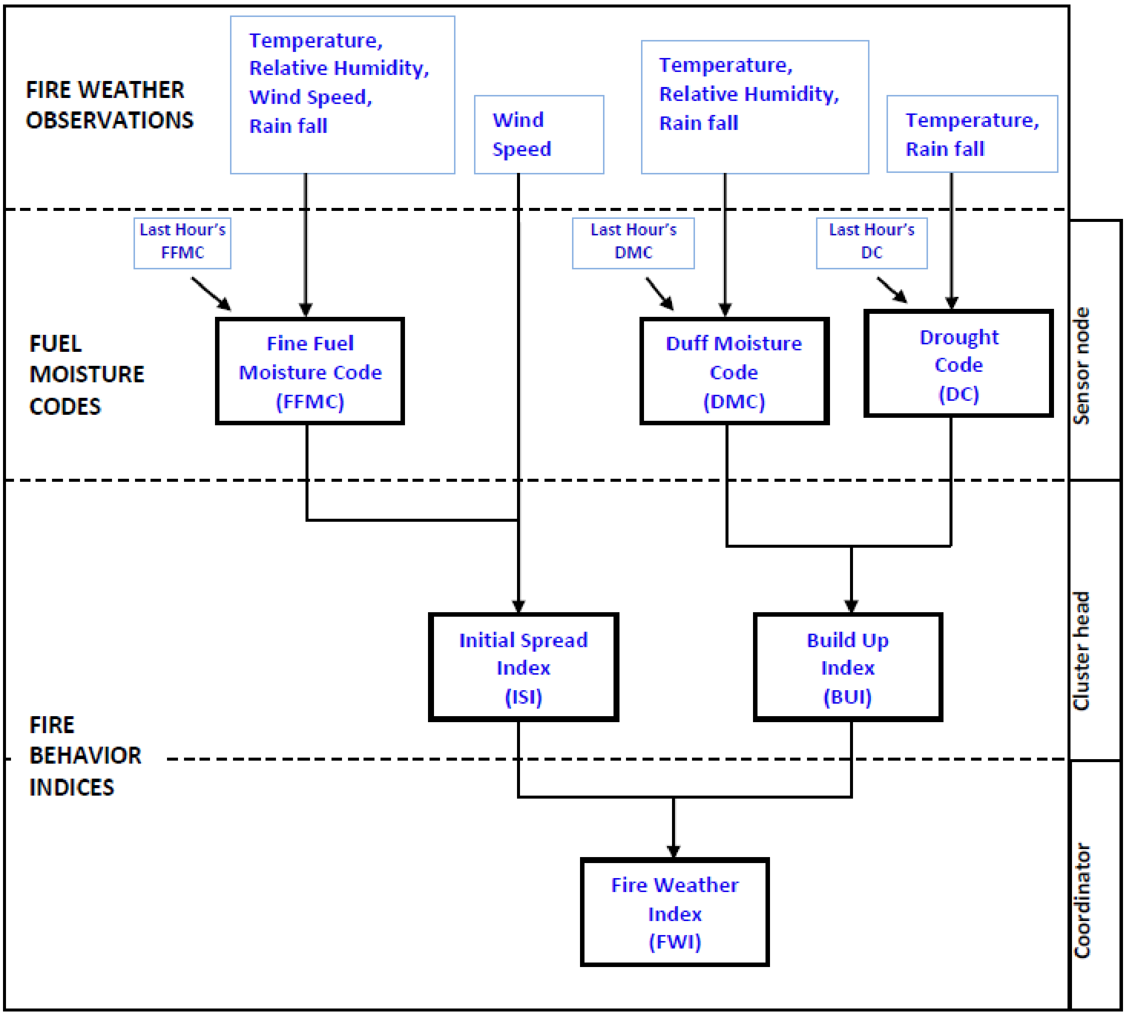


Figure 1: The general structure of the FWI system with modifications for Micro-scale FWI

WSN architecture

A wireless sensor network (WSN) consists of spatially distributed autonomous sensors to *monitor* physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants and to cooperatively pass their data through the network to a main location [15]. However, wireless sensor nodes are resources constrained devices; energy, computational power, and bandwidth are typically limited. Sensing, data processing and communication tasks are the major consumers of the nodes' resources. WSN design requires efficient implementation of these tasks so that un-tethered WSN operational life is long enough for the specific application.

The design of WSN for Micro-scale FWI system considers cluster topology where sensor nodes are grouped into clusters based on their physical location. Each cluster is managed by a more capable node called cluster head (CH). Data routing within each cluster forms star topology. However, the CHs are mesh linked to a network coordinator (NC) so as to extend the network coverage beyond a single hop range. The mesh link also allows for robust data routing by avoiding faulty path to the NC.

The network coordinator is connected to a base station node which is gateway to remote manager node via general public network (GSM, Internet). Remote manager node is a point of fire management decision and fire hazard dispatch for general public user nodes. The architecture of the system is shown in figure 2.

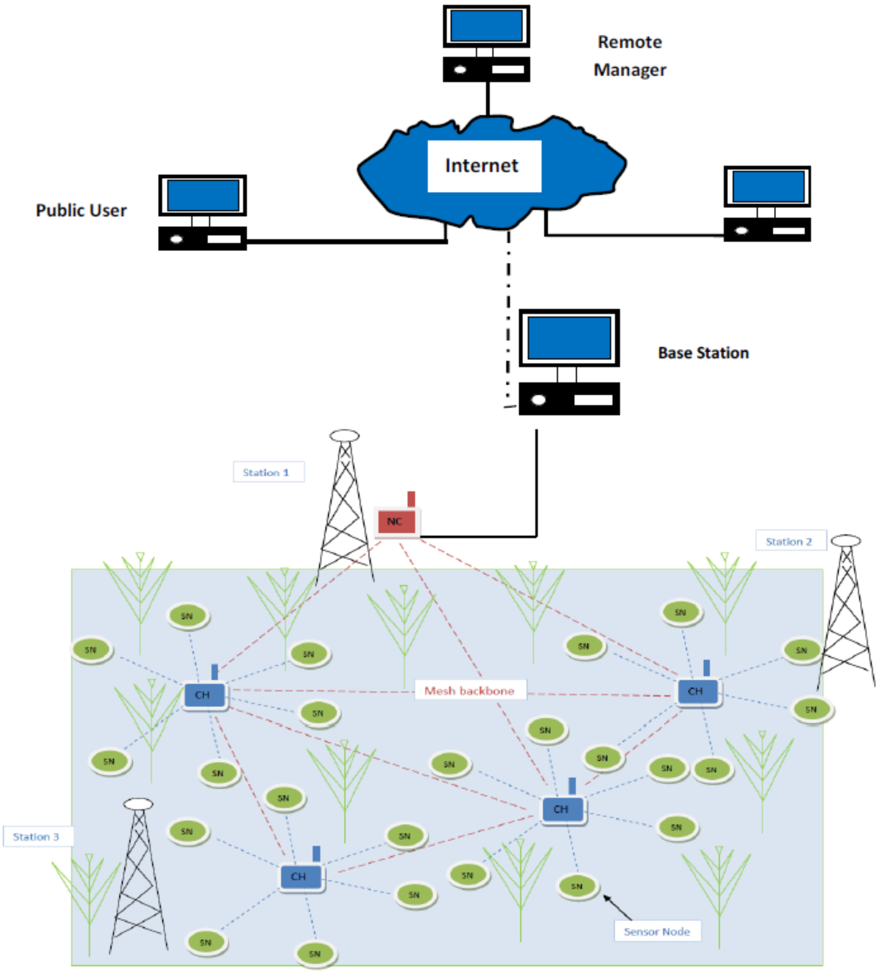


Figure 2: The Micro-scale FWI system WSN architecture

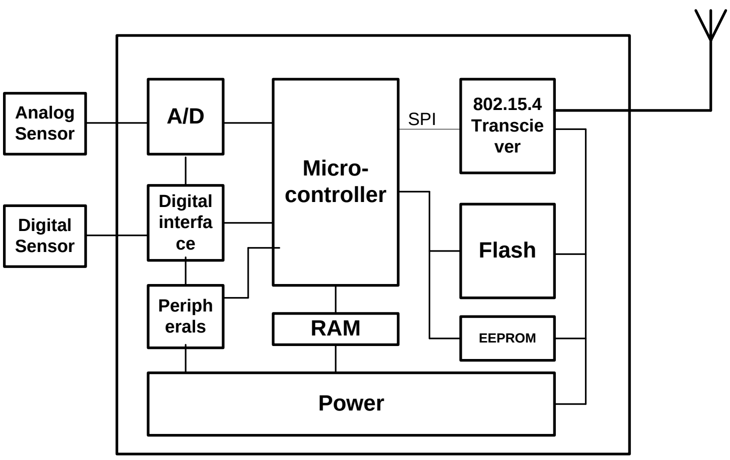
Micro-scale FWI

The Micro-scale FWI system addresses the limitations of the existing FWI system by modelling the FWI system as a distributed wireless sensor network application. Unlike the standard FWI System developed for a macro scale area (e.g. a country or a continent), Micro-scale FWI system does not depend on few large weather stations located tens of kilometres apart for current weather data sources. Current Weather data sources in Micro-scale FWI System are the tiny wireless sensor nodes equipped with various weather sensors and deployed on a given area short distances apart. Due to the short distances between the weather data sources, micro scale FWI does not need elevation information of a given area and hence simplifies FWI system implementation. The Micro-scale FWI system uses wireless capable sensor nodes as weather data sources to form a fire weather network based on wireless sensor network. Distributed in-network data clustering algorithm is used to efficiently compute the FWI indices locally in real-time utilizing a specific WSN architecture (figure 2). Basic components of the Micro-scale FWI system are described below.

Data sources:

The Input to the Micro-scale FWI system is current weather data. Atmospheric temperature, relative humidity, wind speed, and precipitation or rain fall are the weather parameters of interest. Micro-scale FWI acquires these weather parameter data from individual wireless sensor nodes also known as motes. A typical wireless sensor node, an entity of a wireless sensor network, is capable of performing some processing, gathering sensory information, and communication with other nodes in the network [15]. See figure 3 for typical architecture of sensor network nodes.

The main components of a wireless sensor node are a microcontroller, transceiver, memory, power source, and sensors. Power source for the nodes are often batteries. The sheer number of sensor nodes required for most application makes battery replacement expensive [16]. Therefore, using dynamic power management schemes and using batteries rechargeable through solar cells are often recommended. Sensors are used by the node as its means of interacting with the physical world. The continual analogue signal produced by the sensors is digitized by the analogue-to-digital converter (ADC) unit of the microcontroller and is passed on to the application for further processing. As wireless sensor nodes are typically very small electronic devices, they can only be equipped with a limited power source. Hence, sensors have to have extremely low energy requirement in probing the environment.



‘**Figure 3:** Wireless sensor node architecture

Fire weather Network

Micro-scale FWI system acquires current weather parameters data simultaneously from a large number of sources (sensor nodes) densely distributed on a given micro area. The weather data sources are linked via wireless communication to form a structured fire weather network. The weather data acquired by large sensor nodes at different locations in the area monitored need to be transmitted to a base station to be processed and provide fire potential, prediction, and behaviour information to fire managers. The fire weather network structure consists of sensor nodes as data sources, cluster heads as point of data aggregation and false alarm filtering, and a network coordinator as a gateway to the base station.

The fire weather network uses industrial, scientific, and medical (ISM) band radio spectrum in the license-free communication frequencies 433 MHz, 868 MHz, 915 MHz, and 2.4 GHz. A standard IEEE 802.15.4 based ZigBee wireless protocol stack is used for the purpose of evaluating this study. The IEEE 802.15.4/ZigBee protocol enables every node 250 Kbps (kilobits per second) data rate at a very low power of 1 mW (mili watt) for an average transmission range of 100m. ZigBee enables virtually unlimited number of nodes per network.

Data processing

Micro-scale FWI involves distributed computing of the FWI indices. The different nodes of the fire weather network (sensor nodes, cluster heads, and coordinator) are assigned tasks of computing some part of the FWI indices. The WSN architecture (figure 2) coordinates the individual nodes tasks so that the complex computation of the FWI indices can be achieved through minor local computations working together as a whole. The distributed computation method enables fast near real-time fire indices production. The Micro-scale FWI system further embeds incremental distributed FWI information clustering algorithm-SUBFCM [17] throughout the network in order to efficiently utilize the nodes energy and network bandwidth resources and consequently extend the network lifetime.

The sensor nodes are assigned the task of periodically computing local fuel moisture codes (equations 1, 2 and 3) and transmit to their Cluster Head (CH). The CHs are assigned the task of computing fire behaviour indices (equations 4 and 5). Besides the fire behaviour indices, the CHs execute the indices clustering algorithm locally and transmit to the network coordinator. The network coordinator is assigned the task of computing the final FWI index based on the indices received from all CHs. The network coordinator produces global clusters of indices.

The Base station assisted by the coordinator produces periodic virtual clusters. The virtual clusters are clusters of fire hazard rating or intensity mapped onto the exact physical node locations as shown in figure 4. The virtual clusters provide spatial map of the hazard distribution as an overlay to the physical node clusters. The virtual clusters mapped onto the physical nodes' locations map provide geographic distribution of the hazard situation. The virtual cluster could be viewed periodically and could provide dynamic information of the fire hazard situation such as speed and direction of hazard movements. The virtual cluster information can further be utilized to reconfigure the physical cluster for better and efficient WSN resources utilization.

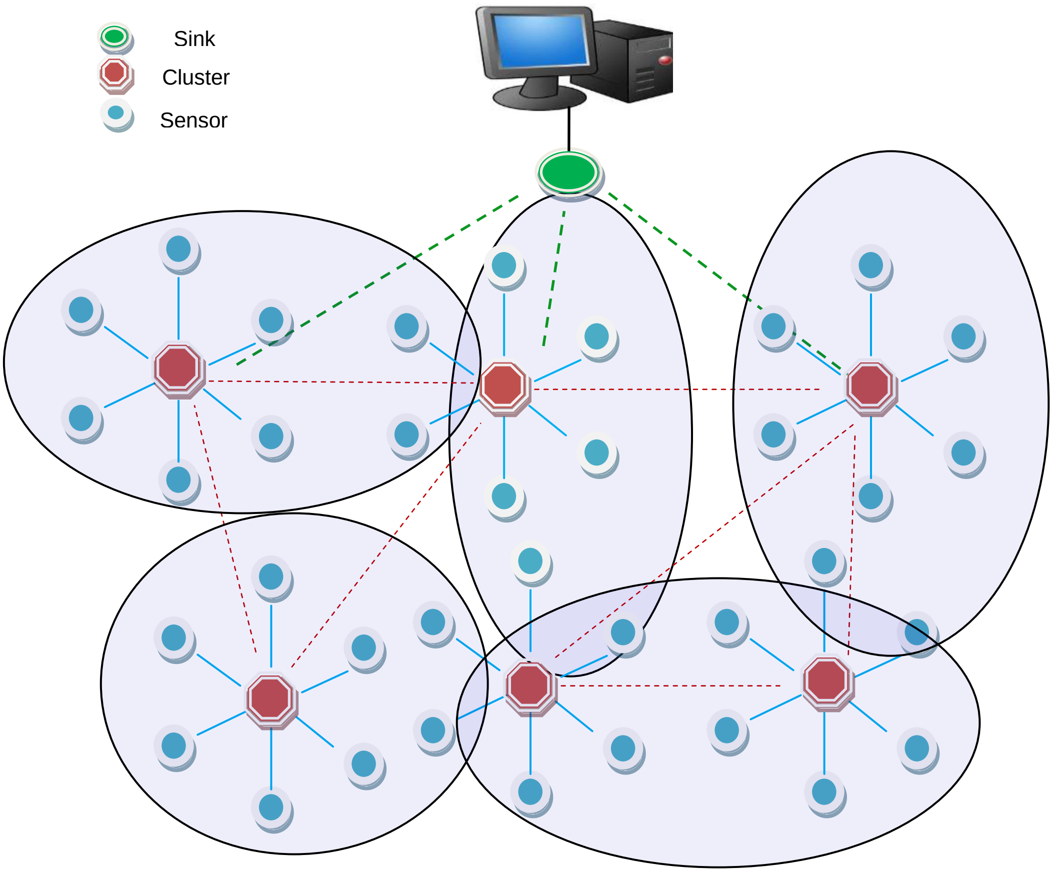


Figure 4: Virtual cluster overlay to the physical cluster

Results presentation

Hourly maps of temperature, relative humidity, wind speed and precipitation have to be computed for each pixel of the grid. For small areas between the sensor nodes, values are computed by interpolating values from their nearest neighbour nodes to produce continuous weather maps. Inverse distance weighted (IDW) interpolation is employed to produce grids of weather values to feed into the FWI maps.

The Micro-scale FWI system Model

The Micro-scale FWI model consists of the weather sensor models linked through TrueTime ZigBee wireless network. The weather sensor nodes cluster organization, data transmit period for each node, FWI processing algorithms and processing time delays are configured through Matlab scripts which are attached to the model through an interface dialog. The model takes the path-loss of the radio signals into account by taking the x and y coordinates of every node as inputs.

The Micro-scale FWI system modelling is done in MATLAB environment utilizing the TrueTime network simulation toolbox. The Model consists of weather sensor nodes sub-models linked through the TrueTime's ZigBee wireless network sub-model.

The weather sensor nodes sub-models consist of functional modules that represent a Kernel, Sensors interface, radio transceiver, localization, and power source. The parameters of these functional modules are set to represent the Texas Instruments MSP430F2274+CC2530 low power ZigBee module powered from two AAA size batteries of each 1.5V, 1200 mAh rating. The sensor module settings are that of Sensirion's SHT15 digital temperature and relative humidity sensor. Some modules include Sparkfun's SEN-08942 weather meter.

The ZigBee wireless network sub-model consist of functional modules to handle radio signal characteristics, network topology, data routing, FWI indices processing algorithm tasks, data processing and transmission delays, and localization.

Simulations and Results

Real weather data sets recorded at several meteorology stations in South Island, New Zealand and obtained from National Institute of Water and Atmospheric Research (NIWA). These data sets are used as benchmarks to validate the system performance and consist of weather parameters (temperature, relative humidity, rainfall and wind speed) along with their corresponding Canadian FWI indices (FFMC, DMC, DC, ISI, BUI, and FWI) collected hourly for the years 1994 to 2004.

The Micro-scale FWI system model described above is set up for simulation. The initial simulation configuration consisted of 16 weather sensor nodes self-organizing themselves autonomously into two clusters; each of these clusters is managed by a cluster head. Once the organization of the wireless network is achieved, the weather sensor nodes acquire weather data from an input file, compute part of the FWI indices, and send to their respective cluster heads every 30 seconds. The cluster head nodes, upon receiving the partial indices from all of their member nodes, enhance the partial FWI indices and transmit them to the sink for further processing. The initial simulation configuration consisted of 16 weather sensor nodes for the sake of fire hazard prediction model sanity check. However, the rest of the simulation consisted of up to 200 weather sensor nodes and 25 cluster head nodes within an area of 1.72 square Km to mimic a naturally dense WSN. In order to investigate the effect of the number of sensor nodes on prediction results, the number of weather sensor nodes involved varied from 16 to 200 during simulations.

A small scale Micro-scale FWI system model is simulated on real datasets for the purpose of model sanity check. A total of 16 closely located weather sensor nodes were assumed to represent 16 sparsely located real weather stations. Weather parameter datasets obtained hourly at 16 stations and were fed to the corresponding weather sensor nodes every 30 seconds. The FWI index computed by each sensor node was logged at the gateway and compared to the actual FWI index from the conventional FWI system. Sample FWI index logged for a single sensor node was compared to the corresponding station for 100 datasets as shown in figure 5.

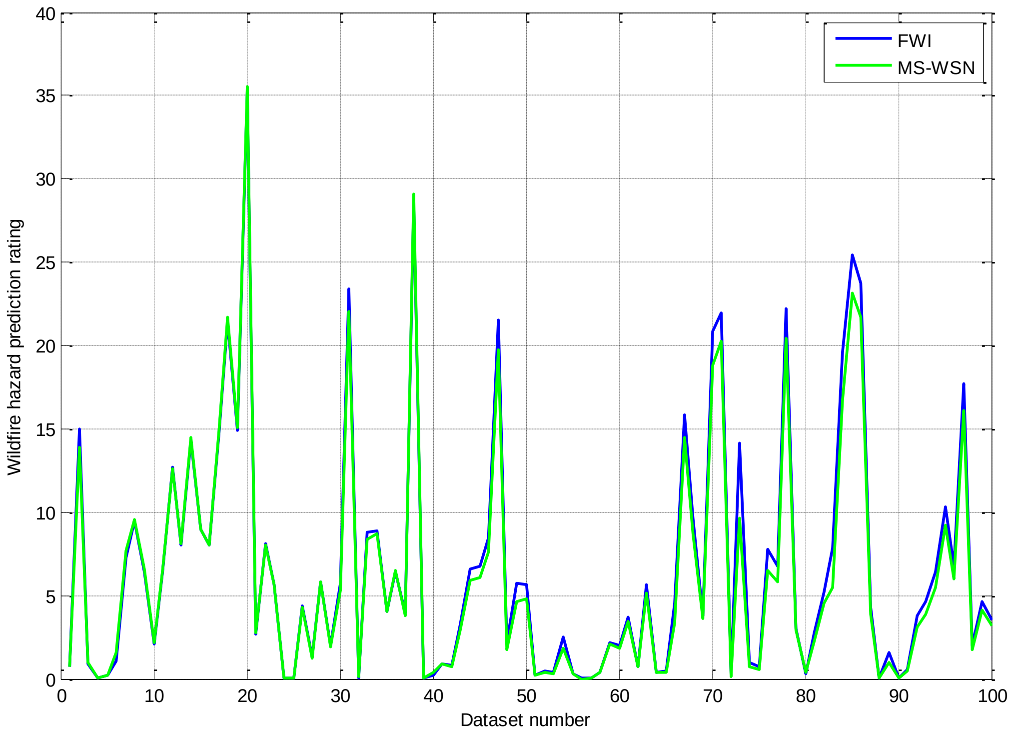


Figure 5: Comparison of Micro-scale FWI and FWI systems FWI index

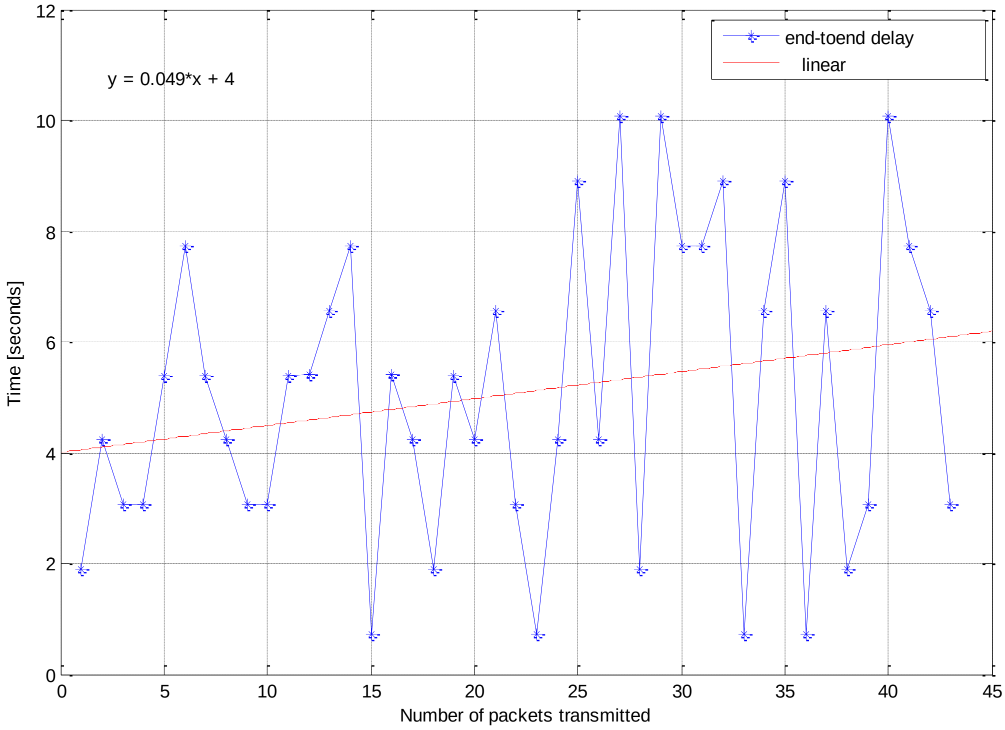


Figure 6: Average end-to-end delay

The average end-to-end delay of the Micro-scale FWI system model is shown in figure 6. Up to 54 weather sensor nodes and 6 cluster heads were competing for the wireless channel; the maximum delay observed was 10 seconds, with an average of 5.0747 seconds.

The Micro-scale FWI system model was evaluated for the amount of data packets lost under different data transmit periods. The results in figure 7 show that the number of packet loss decreases exponentially as sensors transmit data packets less frequently.

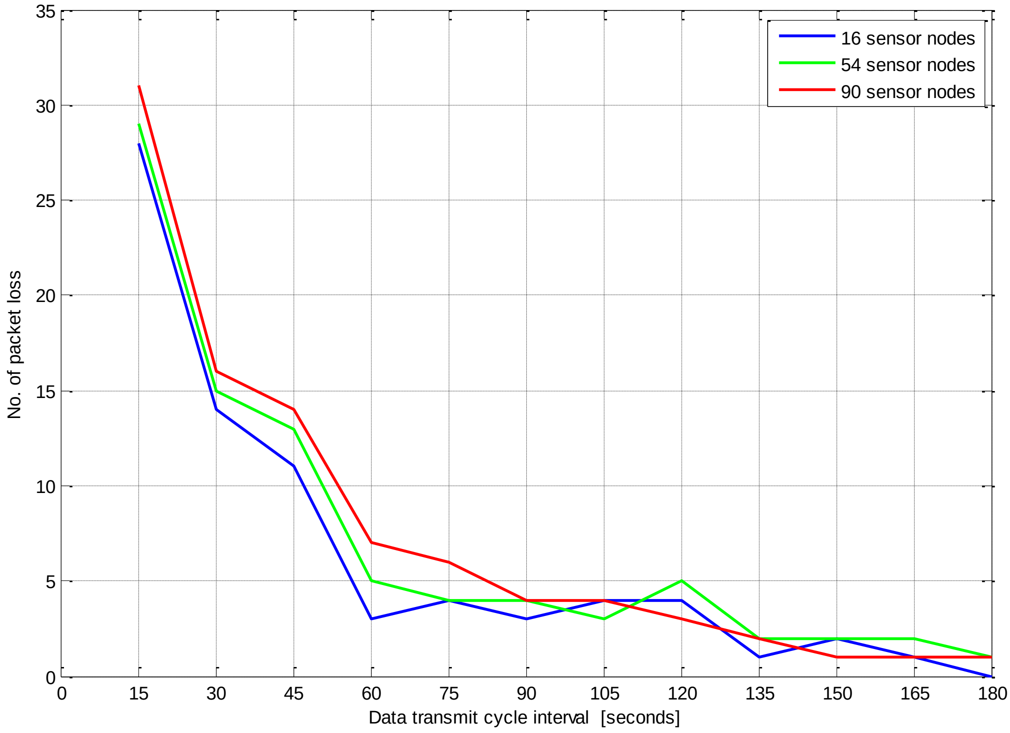


Figure 7: The Micro-scale FWI system Packet loss performance

The model's energy consumption is analysed based on the TrueTime battery model. The battery model computed energy consumption due to kernel data processing, packet transmission/reception, and idle waiting. Two AAA size batteries performance on the Micro-scale FWI system model is shown in figure 8.

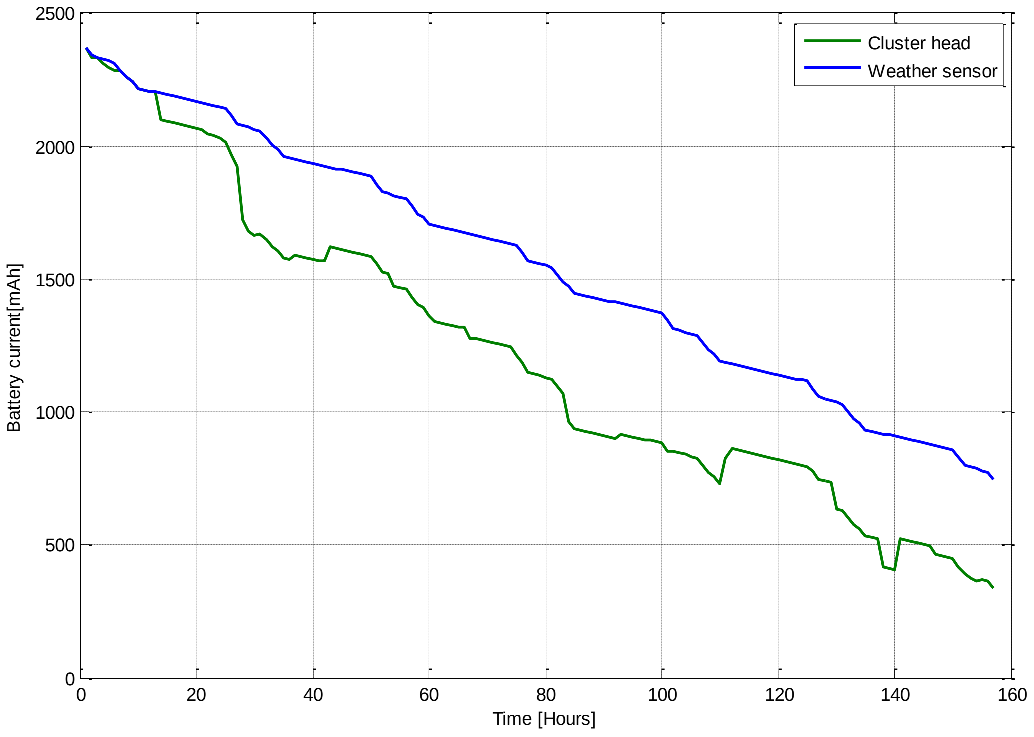


Figure 8: The Micro-scale FWI system nodes energy consumption performance

Discussion and Conclusion

The paper has presented wireless sensor network based Micro-scale FWI system. This is based on TrueTime modelling and simulation software. The MS-WSN model sanity has been verified through real weather datasets. Distributed in-network processing of wildfire hazard prediction based on WSN has several advantages while producing similar results to satellite communication based FWI system. The end-to-end delay, packet loss and energy consumption performance of WSN model have been observed through simulations. The simulation results indicate that for two-tiered WSN architecture, the influence of end-to-end delay, energy consumption and pack loss on the FWI indices results are insignificant. This system offers high spatial and temporal resolution wildfire hazard prediction system which is cost-effective, energy efficient, and easily deployable for emergency situations.

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