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A Forest Early Fire Detection Algorithm Based on Wireless Sensor Networks

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Abstract: Wireless Sensor Networks (WSN) adopt GHz as their communication carrier, and it has been found that GHz carrier attenuation model in transmission path is associated with vegetation water content. In this paper, based on RSSI mechanism of WSN nodes we formed vegetation dehydration sensors. Through relationships between vegetation water content and carrier attenuation, we perceived forest vegetation water content variations and early fire gestation process, and established algorithms of early forest fires detection. Experiments confirm that wireless sensor networks can accurately perceive vegetation dehydration events and forest fire events. Simulation results show that, WSN dehydration perception channel (P2P) representing 75 % amounts of carrier channel or more, it can meet the detection requirements, which presented a new algorithm of early forest fire detection. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Wireless sensor network (WSN), GHz electromagnetic wave, Attenuation model of vegetation, forest fire, Perception channel, Detection algorithm.

1. Introduction

In recent years integrated micro-sensor technology, communications technology, embedded computing and distributed information processing technology, wireless sensor network (WSN) can collaborate in real-time monitoring, sensing and collect information of each distribution, and do processing and transmission of these information, it has broad application prospects in industrial, agricultural and military field [1-3]. In this paper, concrete construction monitoring features, is proposed based on wireless sensor networks and mobile agent (Mobile agent MA) distributed crack monitoring system, the system consists of temperature and strain wireless sensor nodes, base station and remote monitoring center. According to monitoring task the system decomposes it and sent corresponding mobile agent to sensor nodes, achieves data acquisition and information processing to significantly reduce redundant data transmission, and turns the traditional serial processing & centralized decision-making system into a parallel distributed information processing system, it reduces the energy consumption of nodes and improve running speed of monitoring system and reliability and flexibility of decision-making system. Using wireless sensor nodes, system greatly reduces the number of leads, making it easy to install and achieve long-term online monitoring [4, 5].

Electromagnetic waves of operating frequency GHz-class are very sensitive to propagate cumulative attenuation on vegetation water content. Common electromagnetic space attenuation model is divided into Longley-Rice model [6], Okumura model, Clarke model, Hata model [7] and so on. Accuracy of space propagation attenuation model is low, and has not raised relating model to vegetation attenuation. In 1977, according to data of high frequency electromagnetic wave measured by scattermeter [3] and literature [4], Dobson defined the concept of complex media, proposed that vegetation absorption and scattering coefficients are the main factors of attenuation [5-10], and defined absorption and scattering coefficients by complex permittivity, determined high-frequency attenuation mechanisms of vegetation, as well as accurate representation and associated coefficient of vegetation attenuation. Recently in high-density vegetation attenuation field tests, Crossbow company obtained 2.4 GHz electromagnetic attenuation values [11], which values positively correlated with vegetation water content, thus confirming that in electromagnetic wave propagation of high frequency GHz, vegetation water content has precise correspondence to electromagnetic attenuation.

Based on measurements of different vegetation water content, this paper obtained more precise attenuation values of different water vegetation content and determined relationship between channel attenuation and vegetation water content, proposed algorithms based on attenuation coefficient λ which accurately perceive forest vegetation dehydration state. For vegetation dehydration process caused by fire, mainly in early decomposition, heat, smoke, fire, and so on. Through measuring wireless sensor networks (WSN) signal intensity of sensing channel (such as RSSI, etc.) and channel loss statistics, as well as the deployment of WSN, we could achieve monitoring and management of forest fires, vegetation seasonal changes and etc.

2. Design of Wireless Sensor Nodes and Base Station

The remote monitoring system based on wireless sensor networks is to utilize sensor nodes distributed in forest different locations collecting temperature, moisture, strain and other parameters, base station transmitted these data to remote monitoring center for real-time data processing and analysis, users can achieve real-time monitoring and control on site of monitoring centre or via internet terminal, in order to provide decision support for forest fire prevention.

In traditional WSN monitoring system of C/S structure, each sensor node needs to collect large numbers of raw data to remote monitoring center through relay, and monitoring centre makes analysis of these data, processing, and integrated decision. Though node collecting and transmitting in parallel, due to transferring large amounts of raw data, sensor nodes will consume a lot of energy and reduce the service life of nodes; while remote monitoring centre receives data of each node in serial, time required also increases dramatically with the network size, bringing a greater delay. To avoid deficiencies of C/S structure WSN monitoring system, the design of fire monitoring system adopted mobile agent technology for data processing and information transmission, system architecture diagram is shown in Fig. 1.

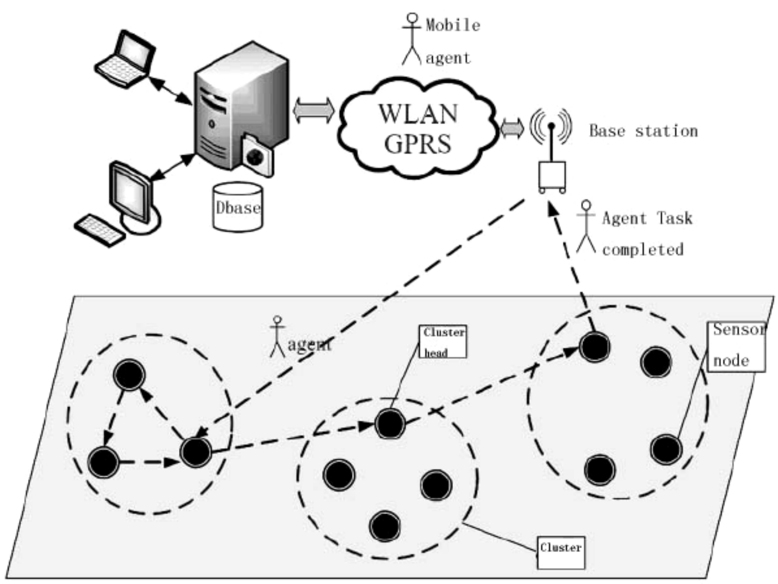

Fig. 1. Architecture of WSN and MA-based monitoring system.

In accordance with certain rules to determine number and location arrangement of sensor nodes, in practical each sensor node needs to dynamically converging multiple clusters, each cluster has a head, cluster head generally have more storage space, more energy power and strong computing. After task assigned, the monitoring center firstly decomposed it into easily realizable multiple sub-tasks according to features and complexity of the task, sends to each sensor node a certain function of mobile agent (a piece of executable code that can carry data, status and other information to move between different systems, and can automatically run when reaching target host), after each node receiving a mobile agent, mobile agent will run at the node for various task, such as starting data collection, processing for collected raw data, and can collaborate to complete complex tasks. After task completed the mobile agent sent results on best path to base station, base station collected data of each node and transmits to remote monitoring centre for making integrated decision. The movement of mobile agent is shown in Fig. 1.

In such a system, many tasks are accomplished on local node through mobile agent, after task completed mobile agent will send intermediate results and state data to the next node (local nodes restore to the original state, ready to perform other tasks), and mobile agent sent results to remote monitoring center, finally monitoring center make comprehensive decision, achieve forest temperature and stress control, and then take measures to prevent forest fires. System effectively solve the problem of transmitting information between monitoring center, sensor nodes and base stations through mobile agent, and solve the nodes problem of insufficient storage space, but also avoid sending large amounts of raw data, greatly saving energy consumption to extend nodes life.

According to Fig. 1, fire monitoring system consists of wireless sensor nodes, base stations and remote monitoring center. Wireless sensor nodes and base station consists of several temperature sensors, strain sensors and corresponding signal conditioning circuit, microcontroller, wireless transceiver module and other components. As shown in Fig. 2, digital processing and control module is using TI's ultra-low-power 16 bit processor MSP430, wireless transceiver module using CC2420, using PT100 for temperature measurement, and BSQ120-l0AA resistance strain gauges has full-bridge strain, and with a compensation plate for ambient temperature.

3. Measurement of GHz Electromagnetic Wave Attenuation in Vegetation Propagation

Electromagnetic waves have two attenuation ways along the dissemination process: distance attenuation and medium attenuation. Wherein free space the attenuation formula is defined by Friis:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2, \tag{1}$$

where P_r is the received power; P_t is the emission power; G_t is the transmitting antenna gain; G_r is the receiving antenna gain; R is the distance between the transceiver, power attenuation is inversely proportional with R^2.

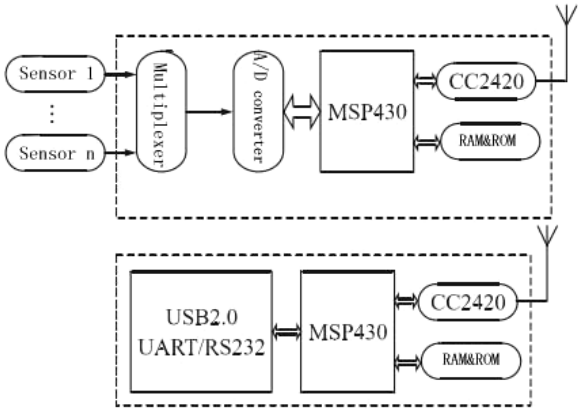

Fig. 2. Diagram of wireless sensor nodes and base station.

Experiments tested in electromagnetic shielding chamber using Agilent E4402B tester, the testing model is shown in Fig. 3. Among them, the cavity's length 1.5 m, width 0.4 m, height 0.3 m, and walls coated with 2 cm thick absorbing layer to simulate electromagnetic wave attenuation characteristics in space of vegetation. 2.4 GHz respectively using single frequency, Bluetooth node, ZigBee node for three electromagnetic environments, and tested in three types of cavity:

1) Cavity A, B are of same size placed with vegetation;
2) Cavity A is placed into small particles of dust with adjustable density (simulated fire fuming stage), while cavity B filled with vegetation;
3) Chamber A, B are all unfilled space.

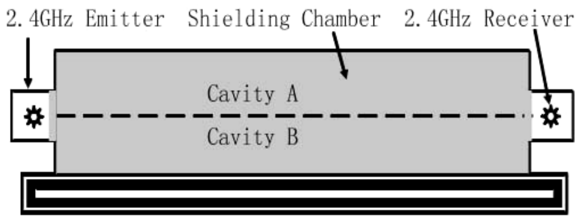

Fig. 3. GHz attenuation test bench for forest vegetation.

Attenuation value is determined by two parts of distance attenuation and vegetation attenuation (not considered antenna attenuation). The ingredients of vegetation include leaves and 14 branches of diameter 1 cm – 10 cm (vertical insertion), withered plants have an equal number; chamber A is poured in three categories: with smoke into dust, water vapour and plants burning residual ash, as shown in Table 1.

In Table 1, experiment 3-5 shows attenuation value of fresh vegetation is 2.5 times bigger than withered vegetation for the larger water content, while GHz electromagnetic wave propagating on the surface of vegetation, the attenuation value is small, but still associated with the freshness of vegetation. Experiment 6 values shows distance attenuation.

Table 1. Attenuation measurements of different vegetation water content.

Name	Cavity A	Cavity B	2.4 GHz attenuation (dB)		
			Single frequency	Bluetooth	ZigBee
test 1	Fresh leaves and branches		2.07	2.10	2.01
test 2	Withered leaves and branches		0.85	0.74	0.90
test 3	Moderate smoke(≈ 2300mg/m^3)	Fresh leaves and branches	0.30	0.30	0.30
test 4	Moisture (fog)		0.30	0.30	0.30
test 5	Dust (Diameter <100nm; 200g/m^3)		0.31	0.31	0.31
test 3.0	Moderate smoke(≈2300mg/m^3)	Withered leaves and branches	0.19	0.19	0.19
test 4.0	Moisture (fog)		0.19	0.19	0.19
test 5.0	Dust (Diameter <100nm; 200g/m^3)		0.19	0.19	0.19
test 6	Unfilled	Unfilled	0.16	0.16	0.16

4. Fire Detection Principle of WSN Sensing Channel

Assumed attenuation coefficient of high density vegetation is L_{forest}, which is higher with larger vegetation water content, while decreasing with water content reducing. If vegetation moisture content dramatic declined in a short time, it has reached a high risk of early fire, or fire has just occurred (maximum attenuation rate).

Vegetation water loss causes propagation attenuation significantly reduced, by measuring signal strength of sensing channel (RSSI) of WSN deployed in the forest, perceived the degree of vegetation dehydration. This attenuation value associated only with the vegetation water content, attenuation period to vegetation growth cycle is fixed, but for fire-burst, drought, massive deforestation, etc., this attenuation cycle can exhibit different characteristics. In the experiment, if L_{forest}, L_{as}, L_{fire} assumed for attenuation values of vegetation's fresh state, withered state, and complete fire state, introducing state characterization coefficient γ, defined attenuation values (distance attenuation) with no vegetation between nodes is L_{range}:

Factor for high density fresh vegetation:

$$\lambda_{forest} = \frac{L_{forest}}{L_{range}} = 12.56 \qquad (2)$$

Factor for high density withered vegetation:

$$\lambda_{as} = \frac{L_{as}}{L_{range}} = 5.31 \qquad (3)$$

Coefficient for fire space mixing smoke and vegetation:

$$\lambda_{fire} = \frac{L_{fire}}{L_{range}} = 1.93 \qquad (4)$$

In formula above, λ_{fire} is the coefficient of fire state, λ_{as} for almost withered coefficient, and λ_{forest} is attenuation coefficient of fresh plants. Vegetation status field determined by λ is shown in Table 2.

Table 2. Λ Range and vegetation status.

	$\lambda \le 2$	$2<\lambda\le 4$	$4<\lambda\le 8$	$\lambda>8$
status	fire flaming	early fire	withered	fresh plants

In period T_{test} given attenuation rate $\Delta\lambda$, which refers to the ratio of sub-sampling attenuation value ΔL to period T_{test}, that is:

$$\Delta\lambda = \frac{\Delta L}{T_{test}} \times 100, \qquad (5)$$

or

$$\Delta\lambda = \Delta L \times 100, \qquad (6)$$

When sampling period T_{test} is far less than fire event cycle, attenuation variation caused by fire incident is a linear process, and take T_{test} as a basic unit, the difference between two adjacent data is attenuation rate. In the practical application of fire detection network WSN, due to sampling period of WSN far less than fire brewing cycle (exothermic decomposition, smoke, fire), attenuation rate determined by two close changes, and $\Delta\lambda$ has a threshold range, when beyond this range, determined fire event.

4.1. Δλ Detection Algorithms

Using $\Delta\lambda$ variation monitoring fire phenomena, the key is to define a reasonable $\Delta\lambda$. Through our practical tests to WSN, T_{test} considered nodes distance and signal strength factor. For Bluetooth, ZigBee node characteristics, select T_{test} = 1h (routing or node's sleeping period less than this cycle), and from experience view when $\Delta\lambda \geq 100$ fire flaming occurs. The reason is that the rapid vegetation dehydration (1h) arise attenuation variation, that is to say, the vegetation is in state of rapid dehydration (drying), thus $\Delta\lambda$ is 182 when attenuation values reducing from maximum value (2.01) to minimum (0.19), and fire occurs in parts of propagation path, so choosing a lower value (100) for $\Delta\lambda$ is experimentally reasonable.

4.2. Vegetation Dehydration Curve within one Year

Channel attenuation value due to vegetation loss of water, attenuation changes with different season of a year, forest vegetation can be divided into three typical structures: bamboo forest, mixed plantation, primeval forest. Testing results as shown in Fig. 4, artificial forest has maximum attenuation variation, indicating vegetation dehydration significant seasonal in plantations, while the other two categories, attenuation's variation rate within one-year is not obvious, their measured maximum $\Delta\lambda$ varied approximately 5-10.

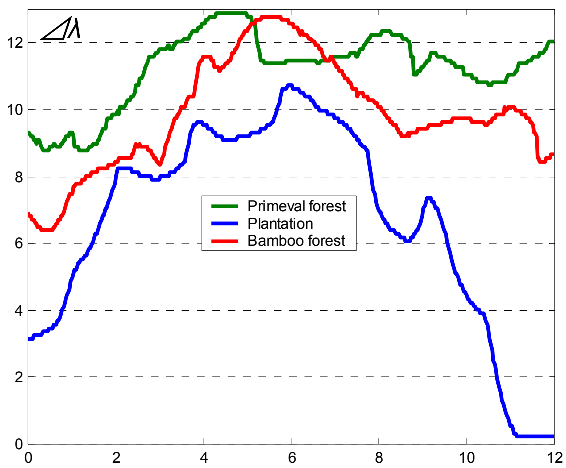

Fig. 4. 2.4 GHz electromagnetic wave attenuation curves within one year.

5. Sensing Algorithm of Highly Reliable Channel

WSN channel will appear in three different situations. The desired channel should be among vegetation being, but practically in nodes selection, excessive attenuation channel is often weak to neighbour nodes, monitoring distance of this part is relatively small; Space between channels often alternated by vegetation and non- vegetation because of terrain or spreading nodes, this channel attenuation is stable but still has some disturbance, this is the common channel mode; For non-vegetation or channels using reflection between nodes is unreliable sensing channel and should be excluded, characteristics of this channel is attenuation substantially not changes or unstably reduces.

These two types of channel above is essential sensing channel to rely on. In these channels, sensitivity of channel I to vegetation is most complete and most reliable, can use $\Delta\lambda$ detection algorithms; channel II requires judging three parameters of λ_{set}, then does $\Delta\lambda$ detection algorithms, too large λ or malformed λ should be discarded.

Assumed the position parameters of WSN unchanged, the expected attenuation and variation of electromagnetic intensity could be the main reference to channel selection. Introducing power identifier between nodes and packets design, provided emission transmission power (sending node), and signal strength identification to receiver, so the actual attenuation coefficient of L_{socket}, λ_{socket} could be determined by:

$$\lambda_{socket} = \frac{L_{socket}}{L_{range}}, \tag{7}$$

Reliable channel selection algorithm with no fire is as follows:

If λ_{socket} less than 8, chose the reliable channel;

If λ_{socket} between 4 and 8, and there may be vegetation space within channels, when $\Delta\lambda$ less than 5, chose the reliable channel and ignoring non-vegetation space; If $\Delta\lambda$ between 5 and 10, existing large non-vegetation space between channels, set to be the reliable channel, the variation of channel attenuation is resulting by the air-vegetation surface;

If λ_{socket} between 2 and 4, existing non-vegetation space between channels, when $\Delta\lambda$ less than 5, it is the reliable channel, at this moment the vegetation between channels has been in an earlier fire state.

Collection of data cycle variation on WSN node, is used to determine the stable attenuation values and error range of channels, determine the scope of $\Delta\lambda$ corresponding to fire state; other value threshold considering channel incredible, if perceived non-fire event, should be excluded.

The selection of highly reliable sensing channel, is to complete reliable using of secondary channels, and pre-identified with power packet mode in neighbor table.

In neighbor-based channel selection, the formation of matching nodes is the main application, which requires adding power identifier in original routing packets, adding matching nodes in neighbor table (determination of reliable channels).

Matching algorithms: Testing electromagnetic waves in receiver of matching nodes, choosing receiver node with higher reception strength than all neighbors, as testing node of pairs. Matching pair nodes selected, noticed closing other neighbors in testing period, then began sensing channel tests. Pseudo-code is as follows.

[Emitter algorithm]
No matching packet arrives;
Turn on Timer;
Number = Round (neighbors number / 3);
If (connect> 0)
If (number! = 0)
{Select matching node of "neighbor node is non-neighbors";
Send matching nodes successful packets;
}
Else
Give up;
Else
Give up;
Timer expires, give up;
[Receiver node selection]
Receive matching packets;
If (requires matching packets)
If (received signal strength is greater than half the neighbor nodes);
Send ACK agreed packets, along with neighbor table ID;
Else
Give up;
Else
If (matching ID = node ID)
Identified matching node;
Give up;

6. Experiment and Simulation

6.1. Channel Experiments

Experiment consists of Scatternet, forming of 8 nodes in 2.4 GHz Bluetooth electromagnetic channel. Nodes communication distance is set to 30 m (fresh thick forest), which has two buffer zone of nearly 2 m. Nodes deployed in the forest area, where A, B, C reference for artificial mixed zone, A0, B0, C0 simulated fired mixed zone, D zone is open shrub area, as shown in Fig. 5.

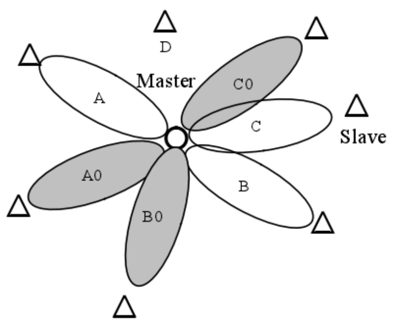

Fig. 5. Test schematic of Bluetooth Scatternet sensing channel.

In Fig. 5 subscript 0 is for fire burning area, test area is divided into 3 m, 8 m area. Combustion is ignited, lighting way is formation of 3 m diameter ignition point, 8 m for two apart 5 m ignition point (post-overlapping), and each ignition assisted 1 kg 93 # gasoline, the time when fire spread to a diameter of required distance was 7 min (3 m), 11 min (8 m). WSN test parameters are shown in Table 3.

Table 3. Bluetooth node channel perception test on vegetation fires.

	Sleep Cycle	Zone 0 (3)	Zone 0 (8)	Zone D
A0	5min	Found after 12 min	12 min	No
A	5 min	No reaction		No
B0	10 min	12 min	12 min	
B	5 min	No reaction		
C0	30 min	30 min	30 min	
C	30 min	No reaction		

NOTE: Bluetooth output is EIRP (Equivalent Isotropic Radiated Power), which selected class I power devices (-30 dBm – 0 dBm, +4 dBm – 20 dBm), reception strength is defined as signal level when BER (Bit Error Rate) 0.1 %.

In this experiment, as vegetation moisture loss after ignition will take some time, and vegetation burnable time is about 207 s, so test areas are reliably detected fires after 12 min. Compared to manual or other detection methods, WSN fire channel detection is reliable and immediate. Fire detection is associated with sleep period, detected about a sleep period after ignition, or burning into sensing range (20 % of P2P distance) detected a fire. The WSN fire experiments reliably perceive fires which perception accuracy is 20 % of radius from the node. In the actual forest fires, fires have a dehydration process, and different regions have different dehydration state, you can accurately find dehydration zone through WSN, and then complete early forest fire prevention and discovery.

6.2. Selection of Reliable Channel

In the communication channels formed by WSN, to determine reliable sensing channel is the basis for ensuring perception window or application. Topological distribution channels of WSN has sufficiently reliable sensing channel, through selection of matching node to sensing channel, the reliable sensing channels can account more than 75 % of existing WSN topology.

OPNET 11.5 is simulation software of Technology. After determined common environmental parameters, OPNET software can simulate channel selection, and output reliable channel ratio (coverage). Routing using GEAR [13] (Geographical and Energy Aware Routing), location and energy aware routing protocol GEM [14] (Graph Embedding), to test the number of reliable sensing channels of different topologies. Specific parameters as described in Table 4.

Where random pipe attenuation used to simulate dehydration attenuation, using power receiving pipe to test random attenuation, the attenuation model determined by $\Delta\lambda$ algorithm, can decide perceived channel with simulation for dense forest environment. Statistical parameters are the ratio of reliable detection number of hop link and total number of hop links. The simulation result is shown in Fig. 6.

Table 4. Parameter of random pipe attenuation.

Random pipe attenuation	0.2
Number of nodes	200
Node spacing	50-400 m
Maximum bandwidth	60 kbps
Antenna Type	Omni directional
Battery capacity	250 mAh
Maximum power consumption	≤23 dBm
Sleep Cycle	20 s
Emulation protocol	GEAR, GEM
Simulation time	1800 s

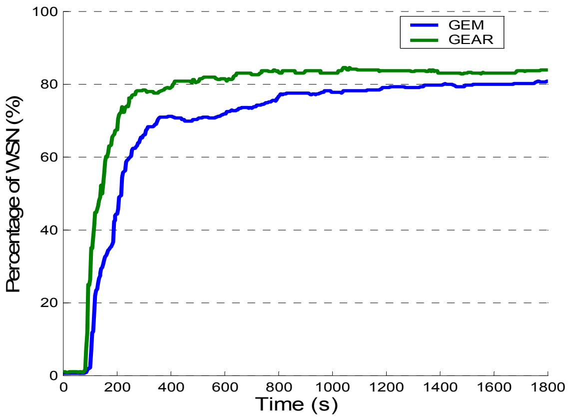

Fig. 6. Simulation results of GEAR and GEM routing reliable sensing channel.

Simulation shows that after 10 sleep cycles (about 200 s), the reliability and availability ratio of channel accounting for over 75 % of established total hop channels, and sustained steadily above 80 %.

6. Conclusions

GHz-level electromagnetic waves have reliable perceptual characteristics on forests and other vegetation, with signal strength analysis of wireless nodes, resulting *Δλ* attenuation algorithm, which can sense fire occurrence and vegetation dehydration process. Through selection of WSN reliable perception channel, when vegetation water content changing along channel propagation path, WSN can quickly perceive it, for large area of fire (20 % of single-hop distance) causes rapid loss of water, can form a real-time monitoring (delayed about sleep cycle).

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