Radio Wave Propagation Through Vegetation

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Abstract—Forest fires are an ever increasing problem for many areas throughout California. In order to effectively fight these fires early detection is key. These fires will be detected using sensors placed in the treetops of a forest. In order to effectively transmit data each sensor unit will also have a transceiver that will receive and output radio frequency (RF) signals. In this paper, the 2.4GHz frequency will be analyzed because it is the only globally allowed frequency. This RF frequency propagation will be analyzed through vegetation while the vegetation is both on fire and not. In addition to analyzing vegetation in different stages of on fire, this paper will also analyze how mote placement within the treetops can affect RF propagation. Lastly, this paper will use this research and analysis to draft a methodology for implementing a mesh network of these motes. This network will be used in a variety of dynamic topographies and climates and must be able to adapt to them effortlessly.

mote-is a wireless transceiver that also acts as a remote sensor

propagation-transmission of motion, light, sound, etc., in a particular direction or through a medium

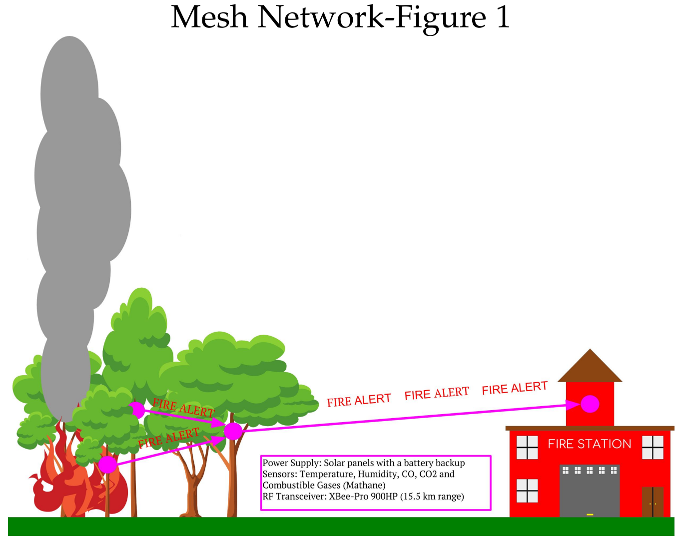
sink-a unit designed to receive incoming events from another object or function

dynamic topography-topography generated by the motion of zones of differing degrees of buoyancy (convection) in the Earth's mantle. It is also seen as the residual topography obtained by removing the isostatic contribution from the observed topography

1 Introduction

In the state of California wildfires are an extremely common occurrence. In 2017, there were a total of 9,133 fires that burned a total of 1,248,606 acres. Two of these these fires alone burned 318,700 acres, destroying 6,706 structures and taking 23 lives. In order to combat this problem a mesh network of transceivers and sensors can use radio frequencies (RF) to transmit their data. This data will be used to alert a fire station of a developing fire. Thus helping firefighters to protect the lives and homes of millions of families each year. This research project aims to analyze the effects dynamic topographies have on Radio Frequency (RF) signals in order to determine the optimal positions of these motes within a mesh network. The radio frequency that will be used in this system is 2.4GHz. A rough diagram of the network can be seen in figure 1 below.

Mesh Network-Figure 1

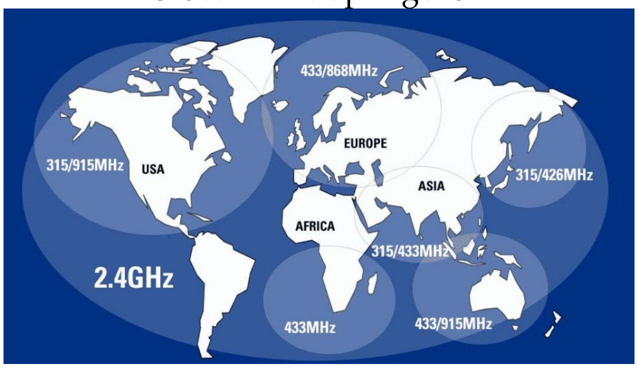


The motes are represented by the purple dots within the treetops. The arrows represent the RF signals transmitting information to the fire station.

1.1 Radio Frequencies

RF waves have a frequency between 30GHz to 3kHz. This range lies between the sound wave and light frequencies. The larger the Hz value the longer the wave. The length of RF waves allow for these waves to travel between 1mm to 100km respectively. In order to reduce interference of these waves certain regions are limited to what frequencies they can use. This breakdown can be easily visualized in figure 2 below [1].

Global RF Map-Figure 2



The only RF that is allowed to be used globally is 2.4GHz.

The 2.4 GHz frequency is the only frequency that can be used globally. Thus the majority of products function using this frequency. The maximum range of this particular wave is 15.5km. Of course this distance will decrease as the wave propagates through different mediums.

1.2 Propagation

Propagation can be defined as transmission of a wave in a particular direction through a medium. At its most basic level this can be expressed through Friis' transmission equation for free space propagation.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$$

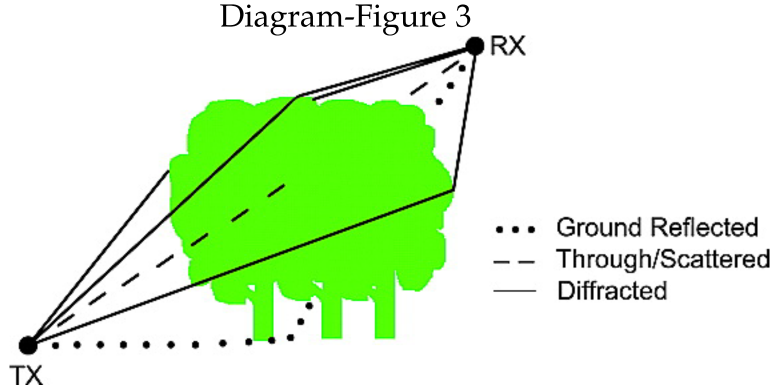
Where P_r is the received power, P_t is the transmitted power, G_t is the transmitter gain, G_r is the receiver gain, λ is the wavelength and d is the distance between the transmitter and the receiver.
The most important factors that affect radio frequency propagation is the output power, environment (including the topography and pollutants), and antenna gain. This paper will focus primarily on the environmental influences on propogation.

2 Research and Analysis

2.1 Factors That Affect RF Propagation Through Vegetation

In the research article, ”Radio Wave Propagation Through Vegetation: Factors Influencing Signal Attenuation”, covers the propagation of three different frequencies through an extensive amount of different vegetation. The most important information from this article for the fire detector project is the 2.4 Ghz frequency thorough vegetation. This article reviews 5 different tree configurations in which the RF signal may encounter. These 5 configurations are line of trees, into vegetation, through vegetation and at the edge of vegetation. RF waves can be passed through vegetation or refracted away depending on the type of vegetation. This can be clearly illustrated using figure 3 below [5].

RF Waves Through Vegetation Diagram-Figure 3



TX represents the transmitting node while RX represents the receiving node.

The paper takes into account the leaf shape, tree height, antenna height and distance to edge. All of these factors can be represented by three equations, one for each the modified exponential decay model, maximum attenuation model and nonzero gradient model. These equations can be written as:

$$Atten = Xf^y d^z$$

Where f is the frequency and d is the vegetation depth in meters.

$$Atten = A_m(1 - exp(-\frac{Rd}{A_m}))$$

Where A_m is the maximum excess attenuation, R is the initial gradient of the excess attenuation curve and d is the vegetation depth in meters.

$$Atten = R_\infty d + k(1 - exp(-\frac{R_0 - R_\infty}{k}k))$$

Where R_∞ is the final gradient of the excess attenuation curve, R_0 is the initial gradient of the excess attenuation curve, k is the offset of the gradient of the excess attenuation curve and d is the vegetation depth in meters.

In addition to all of these affects, wind can also have an effect on the propagation of RF waves. The movements of the branches could cause refraction if the wave were small enough. Fortunately when dealing with the 2.4 GHz wave the wind does not have a large effect on the quality of the wave. This is due to the fact that the 2 GHz waves are much larger than the branches.

2.2 How Those Factors Affect RF Propagation Through Vegetation

The way in which many of the factors described in ”Radio Wave Propagation Through Vegetation: Factors Influencing Signal Attenuation” are elaborated on in the research article ”Analysis of Radio Wave Propagation for ISM 2.4 GHz Wireless Sensor Networks in Inhomogeneous Vegetation Environments”. In order to understand how a wave will behave when coming into contact with one of the previously mentions factors a single wave front is isolated and examined. When a single wave front comes into contact with an object it is split into two separate rays, a reflected ray and a transmitted ray. These rays will be reflected and transmitted differently based on the type of material they come into contact with. Rather than testing all of these different variables in the real world the authors of this research paper opted to use a simulation. This allowed them to change the RF origin placement, receiver placement, watcher, vegetation, and many other factors in order to get results far faster then if they had done it in the real world. The formulas and parameters used for this simulation are as follows [3] :

Formulas for RF Placement-Figure 4

$$\varepsilon_{r\,ash\,wood} = -4 * 10^{-6}t^3 + 0.0002t^2 - 0.0212t + 21.483$$

$$\sigma_{ash\,wood} = 3 * 10^{-7}t^3 - 0.0003t^2 - 0.004t + 7.3238$$

$$\varepsilon_{r\,foliage} = 137h^3 - 69.688h^2 + 23.385h + 1.4984$$

$$\sigma_{foliage} = 1.1541h^3 - 0.5489h^2 + 0.1669h - 0.0004$$

Permittivity and Conductivity Chart-Table 1

Table 1. Material properties in the ray launching simulation.

Parameter	Permittivity (ε_r)	Conductivity (σ) [S/m]
Air	1	0
Concrete	5.66	0.142
Grass	30	0.01
Trunk tree	Equation (4)	Equation (5)
Tree foliage	Equation (6)	Equation (7)

Frequency Chart-Table 2

Table 2. Parameters in the ray launching simulation.

Frequency		2.41 GHz
Vertical plane angle resolution	$\Delta\theta$	0.5°
Horizontal plane angle resolution	$\Delta\varphi$	0.5°
Reflections		6
Transmitter Power		18 dBm
Cuboids resolution		0.5 m

This simulation took into account many different factors. These are clearly laid out in Figure 5 [5].

Radio Wave Propagation Through Vegetation-Figure 5

	Name)					Height	Height
Ravelin Park	Sycamore (Acer pseudoplantanus)	Into	Lobe	In	10 m	3 m	2.5 m & 7.5 m
RAL	Horse Chestnut (Aesculus hippocastanum)	Single	Lobe	In	8-9 m	3 m	5.3 m
RAL	Sycamore (Acer pseudoplantanus)	Edge	Lobe	In and Out	20-25 m	3.5 m	2.5 m & 7.5 m
RAL	Sycamore (Acer pseudoplantanus)	Through	Lobe	In	20-25 m	3 m	5.3 m
QECP	Lawson Cypress (Chamaecyparis lawsoniana)	Through	Needles	In	15 m	3.5 m	2.5 m & 7.5 m
QECP	Common Beech (Fagus sylvatica)	Into	Oval	In	15-20 m	3 m	2.5 m & 7.5 m
J.J.Nurseries	Silver Maple (Acer saccharinum)	Line	Lobe	In and Out	7-8 m	3 m	3 m
J.J.Nurseries	Common Lime (Tilia x Europaea)	Line	Oval	In and Out	7-8 m	3 m	3 m
J.J.Nurseries	London Plane (Plantanus x hispanica)	Line	Lobe	In and out	7-8 m	3 m	3 m

Through this simulation it was found that the 2.4 GHz Wireless Sensor Network was able to transmit and receive information within a 100m radius. An example network can is clearly illustrated in both figure 5 and 6 below [3].

Overhead View 1-Figure 5

Building measurements in order to give reference to the overhead view.

Overhead View 2-Figure 6

At the center of the orange and green circles are motes. The circles represent the outer range of these motes.

As long as the transmitter and receiver are within 100m the range at which information was lost was below 5% this will be considered a reliable network. For the network in figure 6 to be considered a reliable network a third mote must live within the overlapping range circles. This section is colored yellow. This large radius accompanied with the low information loss rate maxes this type of RF transceiver ideal for transmitting information through vegetation.

2.3 Factors During a Fire

While my research focuses on how RF signals propagate in the forest, it is imperative that these sensors still work when the air is filled with smoke. The Savanna wildfires are some of the most intense fires in the world. Because it is imperative that the mesh network works in even the harshest conditions it is best to prepare it for worse conditions than are expected. For this reason the research done by the authors of ”Plant Alkali Content And Radio Wave Communication Efficiency In High Intensity Savanna Wildfires” is vital. Wildfires release ionized gases trapped within alkaline the earth metals present in the vegetation. This gas causes the RF signals to experience an increase in interference. This can be represented by the following formula:

$$\gamma = \alpha_{\mathrm{f}} + \mathrm{i}\beta_{\mathrm{f}},$$

where

$$\alpha_{\mathrm{f}} \cong \frac{v_{\mathrm{eff}}}{2c}\left[\frac{\omega_{\mathrm{p}}^2}{(\omega^2+v_{\mathrm{eff}}^2)}\right]$$

and

$$\beta_{\mathrm{f}} \cong \frac{\omega}{c}\left[1+\frac{\omega_{\mathrm{p}}^4}{8(\omega^2+v_{\mathrm{eff}}^2)^2}\frac{v_{\mathrm{eff}}^2}{\omega^2}\right]$$

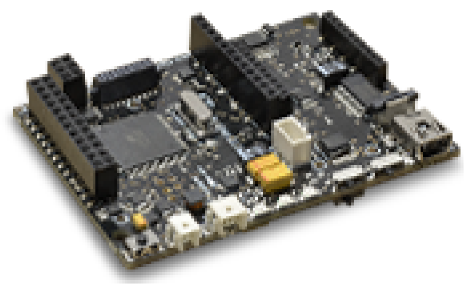
Radio wave propagation is related to the rate at which electromagnetic energy is lost and the wave refraction through the attenuation and refractive index respectively. If an RF wave was to pass within 2m of an area in which the fire exists then it will begin to lose power. At 950 Kelvin only 1% power loss is experienced. However at 1050 Kelvin this jumps up to 12% and by 1150 Kelvin 69% of all power from the wave is lost. Of corse as these waves get closer and closer to the fire the power lost becomes greater and greater.

3 Application

3.1 Methods and Expected Results

Gases pro boards are a part of Libeliums Waspmote family. These boards are small and low power, yet capable of using all the sensors we would need to both detect a fire and keep our firefighters safe.

Waspmote-Figure 7



Waspmote Board [4]

The sensors being used within this design are temperature, humidity and pressure, CO, CO, O and combustible gases. The sensor responsible for temperature, humidity and pressure as well as the sensors for CO, CO and O will be used to detect the fire.

Gases-Pro Board-Figure 8

Sensors used to detect various gasses. [4]

When a fire is started several different factors monitored by these sensors will change drastically. Temperature and levels of CO and CO will rise sharply. As these levels occur O levels will begin to decrease. The fire station will be alerted of the fire once the levels of CO and CO as well as the temperature begin rise to a level that would indicate a fire. The sensor responsible for temperature, humidity and pressure as well as the sensors for O and combustible gases will be used to ensure fire safety. Temperature, humidity and oxygen levels can help firefighters understand how quickly a fire is going to spread, thus allowing them to keep firefighters at the correct distance, far enough away to be safe yet close enough to effectively fight the fire. From the O sensor reading the firefighters will be able to understand the level of breathability where the fire is occurring and the surrounding areas. Lastly, the combustible gases sensor will notify the firefighters if there are any of these gases in the area of the fire or in surrounding areas which allows them to prevent the ignition of these gases or to take action in the event of a combustible gas being ignited.
These boards will be linked to one another in a mesh network using the XBee-Pro 900HP.

XBee-Pro 900HP-Figure 9

Transceiver used to send and receive RF signals. [4]

This board will use a RF signal with a range of up to 15.5 km. While RF signals are great for length they are easily disrupted by dynamic topologies. This problem can be solved by using a mesh network. This way each mote is capable of relaying data to one another and to the sink. The combination of the long range RF signal and the mesh network allow for the flexibility to use a small number of sensors in open areas where the fire threat is low and a larger number of sensors in clustered areas where the fire threat is high. The sink will relay all data collected from the sensors on the motes to the fire station.

Meshlium-Figure 10

Sink used to recieve all information from all motes and relay it to the firesation.

The sink will be used to compile all data received from each mote and seamlessly transmit it to the fire station as easy to read data. Features available to the firefighters include access to all data in real time as a collective system and each mote individually. An immediate alert of the exact location of the fire will be sent if at any time any of the motes readings increases above or decreases below a certain threshold. An immediate alert of the exact location of the mote will also be sent if at any time the motes solar or battery power is beginning to fail. Future implementations will allow the firefighters to monitor environmental conditions in order to assess fire risk in a particular area. All of the hardware will be encased within a housing capable of keeping out the elements while allowing in the appropriate cues to reach the sensor. This ensures the longevity of the equipment as well as the accuracy of the readings of each individual sensor of each mote.

From each of these elements we can expect a simple, easy to use mesh network that remains flexible in the harsh conditions of the wilderness while providing reliable and accurate readings to the firefighters so they can have the best opportunity possible to fight wildfires. The ever growing amount of sensors compatible with this board allows for a huge potential in the upcoming years for a large increase in functionality without having to replace the entire system.

4 Conclusion

This paper began by identifying the main factors that affect the propagation of RF waves through vegetation. These factors include leaf shape,tree height, antenna height and distance to edge. Luckily the influence these factors have on RF can be easily expressed through three equations. From these equations a simulation can be ran in order to test countless environments and vegetation types. This simulation also takes into account environmental factors such as the permittivity of air, trees, grass and other forms of vegetation. The reason these are taken into account is to understand how these RF waves will be reflected. This simulation provided the answer to how vegetation affects the propagation of RF waves.

The results from this simulation show that as long as the motes are within 100m of one another there will be a reliable connection. As vegetation density decreases the range will increase all the way to a range of 15.5km when the motes are in the line of sight from each other.

This allows for the mesh network to be extremely flexible in order to adapt to a limitless number of terrains, environments and conditions. This includes a variety of extreme climates and topographies. Motes can be placed in any arrangement in with an emphasis on fire detection (high density) in areas of high risk or maximum coverage in ares of low risk (low density).

Unfortunately everything changes when this vegetation is on fire. Due to the increase in ionized gas during a fire the RF wave propagation decreases dramatically. The RF waves will lose power if they travel within 2m of the ionized gas. They will also lose almost 70 % of all power once the temperature reaches 1150 Kelvin or higher. This would render any motes affected by this temperature unusable.

This is another area in which the mesh application of the network is vital. If a a network of motes have been cutoff from the fastest way to the sink for whatever reason, they will be able to communicate with motes further away in order to navigate around the obstacle interfering with the non-functional mote.

All in all this information will help in the development of a mesh network of sensors that will instantly notify a fire department of a forest fire. The most important part of this mesh network is that the motes are able to freely communicate with one another. In order to place the motes in optimal locations RF propagation through vegetation must be understood. Once this system is properly implemented firefighters and citizens alike will become musch safer.

Acknowledgements

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