Radio Experiments With Fire

Jonathan Boan, *Student Member, IEEE*

***Abstract*—Radio communication has become an important tool to aid in combatting wildfire. In this letter, we consider the effect of fire upon radio propagation. Results are presented of broadband radio propagation measurements involving three small-scale fire experiments. Measurements reveal that particular frequency bands are affected by fire, being attenuated when fire is present. Ionization, present in the flames, is identified as the major cause of attenuation on radio propagation.**

***Index Terms*—Bushfire, fire, forest, radio propagation, wildfire.**

I. Introduction

WILDFIRE is a common problem throughout many parts of the world and communities allocate copious amounts of personnel and resources to combat it. The introduction of radio communications to fire fighting has greatly aided the coordination of resources and the broadcast of important information to fire fighters. As a result, services are becoming more responsive and effective against wildfire. In Australia, however, there is a growing concern about the reliability and degradation of radio communications in these extreme conditions [1]. In this letter, we consider the effects of small-scale fire upon radio propagation. This letter is part of a broader program that aims to understand the effect of a range of fire situations upon radio wave propagation.

Flames have been known to have interesting electrical properties for well over a century. Early studies show flames are conductive, possessing charged particles created as a product of combustion [2]. One technique used to quantify the amount of free electrons in flames even involves microwaves [3]. Ionized electrons interact with microwaves causing attenuation and dispersion. Sugden *et al.* has used this technique to further investigate the effect of adding metal salts to flames [4]. Recently, Heron [5] has extended this theory to plant life, arguing that sufficient quantities of alkali salts are naturally present in plant life to generate significant electron populations to affect VHF and UHF radio communications. Alkali metals exist as trace elements in plants, vital to growth and overall health. In Eucalyptus trees, alkali concentration is greater in the extremities of the plant, such as the bark, leaf, and branch structure [6]. As these extremities are some of the first components to be burnt, such minerals are easily transported into the combustion zone.

The environment surrounding a fire also contributes to radio wave propagation. Large temperature gradients and changes in the atmospheric gases dramatically affect the refractive index. Subrefractive conditions are setup that cause radio energy to bend away from the ground, reducing signal strength of ground based units [7]. Although it is not expected that refractive conditions will contribute over the small distances used in this experimental campaign, it is plausible that such scenarios will exist within wildfires with sufficiently long fire fronts.

Radar observations of smoke plumes demonstrate [8] another propagation mechanism resulting in signal degradation. Scattering, caused by particulate matter swept up by the fire, can contribute by absorbing and redistributing radio wave energy. It has been noted, however, that scattering caused by the turbulent atmosphere surrounding a smoke plume also greatly contributes to the scattering of radio wave energy [8]. In wildfires large amounts of smoke are generated which disturb large portions of the surrounding atmosphere.

In this letter, we present results from a number of small-scale radio experiments involving fire. Since the fires are small in nature, our major focus is on understanding the effects of ionization. Radio communication has been reported as being degraded when having to propagate through a flame front [1] and this scenario is the focus of the present study. Section II describes the experimental setup that is used and the characteristics of each fire. Section III illustrates some typical results for three popular communications bands. Section IV includes some discussion, and possible explanation, for the major features of these fire experiments.

II. Experimental Procedure

In the experiments the radio signal strength was monitored over short distances (typically 6 m to 20 m). Fig. 1 is a diagram of the experimental setup for each fire. Discone antennas are used to achieve reasonable performance over a broad frequency range from 100 MHz to 1 GHz. A signal generator with power amplifier is located on the transmit side and a spectrum analyzer is located on the receiving side. A laptop computer was used to record the signal strength measured by the spectrum analyzer. Frequency points are acquired every 500 kHz over the frequency range (100 to 1000 MHz), every 8–12 s. In addition to this, a camera was used to take regular photos of the scene. Visual readings allowed propagation events to be related to physical conditions in the fire.

Fire A was the first fire experiment performed in this campaign. It was performed on a different day to the other fires and is the smallest of the three. These differences allow comparisons to be made concerning the effect of fire size and burning conditions. The fuel used is mostly eucalyptus ground litter, including branches and leaves. Hydrocarbon fuel was used to evenly ignite the fuel heap. For this fire, the receive and transmit antennas were placed approximately 1.5 m from the base of the fuel heap.

Fire B and C were performed at another location and are substantially larger compared to Fire A. They present a good comparison between fires of similar fuel size and burning conditions.

Manuscript received February 8, 2007; revised June 5, 2007.

The author is with the School of EEE, University of Adelaide, Adelaide SA 5005 Australia. (e-mail: jboan@eleceng.adelaide.edu.au).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LAWP.2007.902809

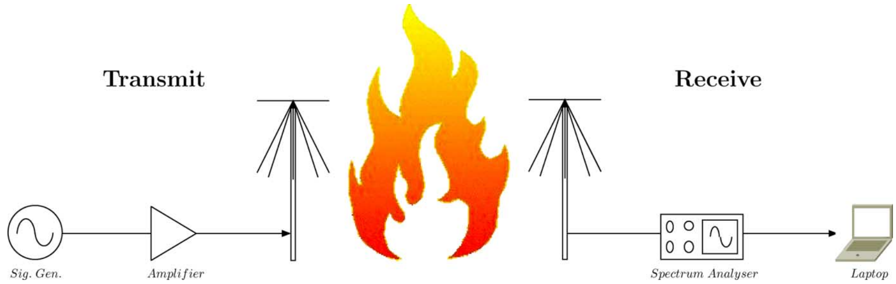

Fig. 1. Experimental setup.

TABLE I
FIRE DIMENSIONS

	TX/RX Height	*Fuel Height*	*Fuel Diameter*	*Additives*
Fire A	1.6m	1.5m	3.0m	None
Fire B	1.8m	3.6m	7.5m	None
Fire C	1.8m	2.8m	7.0m	K_2SO_4

The fuel heaps were ignited evenly around the base with no assistance from hydrocarbon fuels for ignition. Each fuel heap was composed of eucalypt branches and leaves from the local surroundings. Antennas were placed approximately 5 m from the base of the fuel heap for both fires.

As an addition to Fire C, 2.5 kg of K_2SO_4 in the form of small pellets were evenly distributed over the fuel heap. The function of this additive is to increase the concentration of potassium (K) in the combustion zone and, therefore, exacerbate the effects of ionization. Table I provides a summary of the fuel and fire characteristics.

III. Experimental Results

Results from each fire are displayed in three frequency bands. Frequency band 1 encompasses frequencies from 160 to 180 MHz. It represents a typical VHF emergency communications band. The power time profile for each fire is shown in Fig. 2. Band 2 includes frequencies from 400 to 450 MHz. It provides the response of a typical UHF emergency communications band. The power time profiles for band 2 are shown in Fig. 3. Band 3 encompasses frequencies from 850 to 950 MHz and is shown in Fig. 4. It represents one of the popular communication bands used for mobile telephones.

For each measured time sample, an average signal strength was calculated for each band. All time samples were then shifted in time such that ignition denotes zero seconds. This splits our time profile into a "preignition" state and a "postignition" state. A stable period of time with minimal physical movement was then taken from the preignition period and used as a reference. This reference calibrates our absolute signal strength to a preignition relative signal strength. In some plots a noticeable fluctuation in the signal strength exists in the preignition period. This is due to fuel heap preparation, which includes preburning grass in the vicinity of the fuel heap, spraying the ground surrounding the antennas with water for protection and human involvement in physically igniting the heap. Fire B particularly is affected by this in the plots. (Note that a very stable period of time prior to preparation was used as reference, but for sake of display clarity, the results have been truncated.)

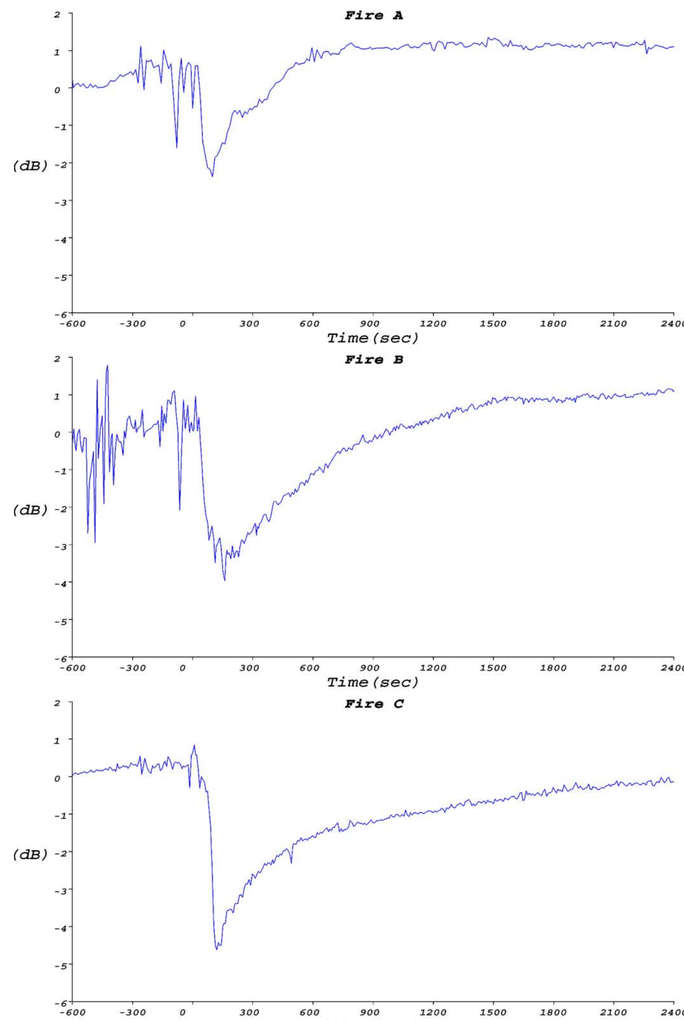

Fig. 2. Relative signal strength of frequency band 1–160 MHz to 180 MHz.

Each of the figures have a similar time power profile. At zero seconds ignition occurs and a sharp drop in signal strength is experienced. This trough deepens as fire intensity builds and then slowly subsides as the fuel heap reduces. Eventually a stable postburn level is reached once the majority of the fuel has been burnt and fire intensity decreases. Postburn signal strengths are relatively stronger than preignition levels due to the destruction of the fuel heap during burning. (The actual effect of fire is masked by the reduction of the fuel heap.) There are, however, propagation effects that can only be explained by the fire itself.

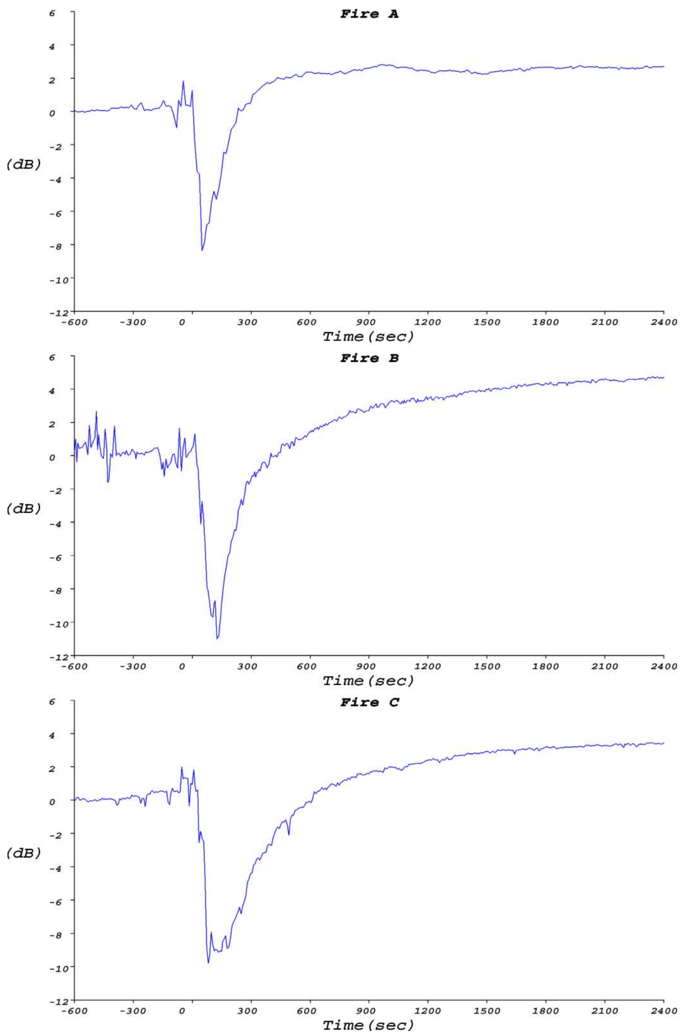

Fig. 3. Relative signal strength of frequency band 2–400 MHz to 450 MHz.

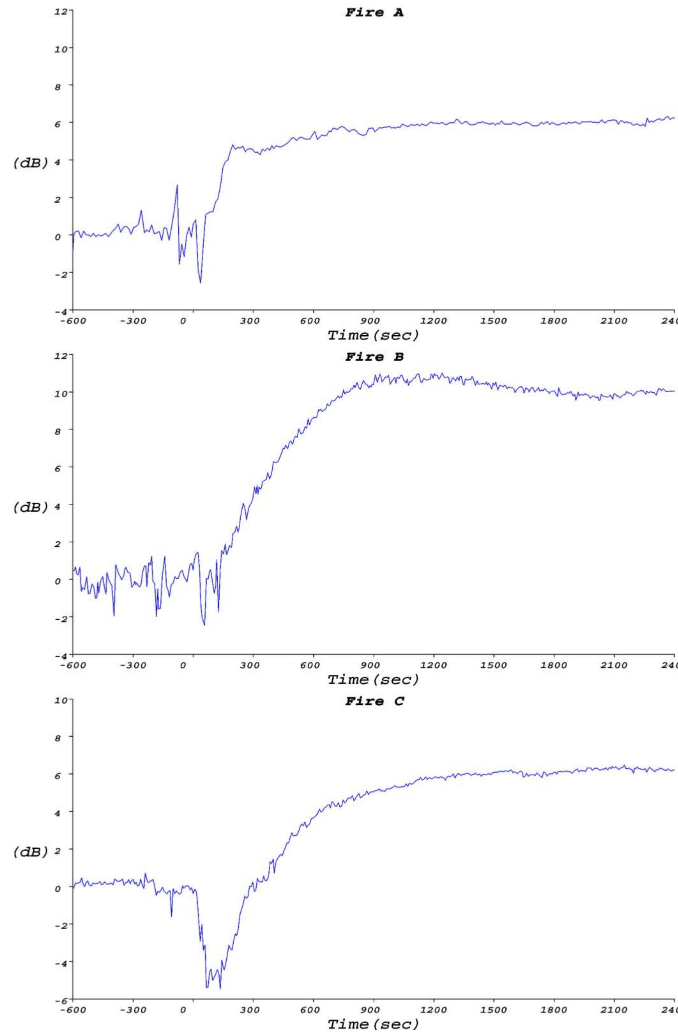

Fig. 4. Relative signal strength of frequency band 3–850 MHz to 950 MHz.

Band 1 measurements, shown in Fig. 2, are the least affected by fire. Even for this, they show a deviation of at least 3 dB less than that caused by the fuel heap.

Band 2 measurements, shown in Fig. 3, are the most affected by the fire, showing the greatest loss consistently in each fire. The duration of this loss increases for each fire. It takes approximately 5 to 10 min to recover to preignition signal strengths. This is one of the intriguing characteristics observed in this experimental campaign.

Band 3 seems largely unaffected by the presence of the fire, but most affected by changes in the fuel heap. This seem consistent with increasing disparity between postburn and preignition signal levels as frequency increases. Fire C is an exception to this behavior and is affected by the fire for a reasonable period of time. The use of additives to the fuel heap can assist in explaining this behavior.

In Table II, values of maximum attenuation are included for each frequency band and fire. Comparing Fire A and B we observe a similar level of attenuation on Bands 1 and 2, despite the discrepancy in fuel heap sizes. On Band 3, a difference in attenuation does occur for each fire but when we further investigate the time profile plots in Fig. 4 we see this initial drop in signal strength (only captured on one sample) is very limited in time, for Fire A and B, compared to the sustained attenuation on Band 3 seen in Fire C.

TABLE II
MAXIMUM ATTENUATION

	Fire A	Fire B	Fire C
Band 1	-3.3dB(180MHz)	-3.7dB(180MHz)	-6dB(180MHz)
Band 2	-12.5dB(418MHz)	-14.4dB(446MHz)	-15.4dB(408MHz)
Band 3	-0.7dB(947MHz)	-4.7dB(921MHz)	-7.2dB(874MHz)

IV. DISCUSSION

The most intriguing part of these results is their consistency over different sized fires and under different conditions. Each band has a similar response over all three fires. In trying to understand factors that affect radio propagation, let us assume the scattering effects are minimal. This seems valid with the small distances involved and the lack of smoke on the line of sight signal path.

The main mechanism dominant in these experiments is ionization [5]. Ionization causes free electrons to exist in the combustion zone. The size of the electron population is controlled by the density of ionizable material (in particular potassium) in the combustion zone. The process can be mathematically expressed using the Saha equation, which predicts the abundance of electrons in a volume is related to the density, temperature, and chemical properties of the element. The collision frequency of the plasma is generally quite high due to atmospheric pressure and gas constituents [9] and is of the order 10^{11} collisions per second. The plasma frequency is related to the square root of electron density.

In order for this plasma to be sustained, a constant intake of material is required and sufficient thermal energy is needed to excite electrons. Just after ignition we have the most promising conditions for a substantial plasma to be generated. The temperature and intensity reach their climax and fresh plant material is still being swept into the combustion zone. Furthermore, this period of time correlates with maximum attenuation. After this climax, the signal strength recovers as the amount of fresh material reduces and hence the intensity of the fire. As aforementioned, following this portion of time the effects of the fuel heap collapsing become the dominant mechanism affecting propagation (i.e., the signal is no longer obscured by the fire). Visible movement of the fuel heap in Fire A is noticeable approximately 50 s after ignition, the heap then continues to depreciate to a minimum about 400 s after ignition. This is indicative for Fire B and C, but the times will differ due to the large size of the original fuel heaps.

For typical values of the temperature (around 1300°K to 1600°K [5]) and typical potassium content (0.09%) for the fuel, the plasma frequency will be in the region of several hundred megahertz. Due to the high collision frequencies, however, collision will dominate the refractive index ($n \simeq 1 - j\sigma/2\varepsilon_0\omega$, where $\sigma \simeq N^2\varepsilon_0/m\nu$) which implies the same level of attenuation across all measured frequencies. Using a cold plasma slab model at the peak of the fire, the attenuation constant for propagation through the combustion region can range from 0.5 to 19 dB/m for the above temperature variation. Diffraction around and over the fire will, however, enhance the signal strength at the receiver. This diffractive enhancement will increase with wavelength which explains the difference in attenuation between Band 1 and 2. For a simple absorbing screen calculation with a representative height of the fuel, diffraction will account for about 4 dB difference in signal strength between each band. This does not however, take into account the propagation around the fire. The observations in band 3, however, are outside the scope of the above explanation.

In application to wildfire, the problem becomes a great deal more complex in scale and fire intensity. One of the major concerns is the constant moving of the fire front and therefore, intake of fresh plant material. This can possibly lead to sustained levels of attenuation as more fresh material is swept into the combustion zone. From this experimental work there is a strong indication that frequencies from VHF to UHF can be attenuated in the vicinity of the flame front. It is largely unknown, however, whether these findings will directly translate to larger scale fires and this is an area for future work.

A theoretical treatment of this problem is already in progress. Current propagation techniques [10] are already being used to explain these experimental results. A more complex model [7], [11] is also being pursued for large scale propagation studies and to understand the three dimensional facets of this small scale problem.

V. Conclusion

The experiments described in this paper have shown that when naturally occurring plant life is burnt it has a significant effect upon radio propagation. In particular, VHF and UHF communication bands are low enough in frequency to interact with ionized electrons present in the fire, causing attenuation. Within this group of affected frequencies higher bands, such as UHF, are identified as dangerous due to diffractive recovery effects not being as strong. More experiments and modeling are planned to extend our understanding of the effect of small-scale fires upon radio propagation in wildfire environments.

References

[1] B. Griffiths and D. Booth, "The effects of fire and smoke on VHF radio communications," Country Fire Association, Tech. Rep. COMM-REP-038-1, 2001.

[2] H. F. Calcote, "Mechanisms for the formation of ions in flames," *Combust. Flame*, vol. 1, p. 385, 1957.

[3] J. Schneider and F. W. Hofmann, "Absorption and dispersion of microwaves in flames," *Phys. Rev.*, vol. 116, no. 2, p. 244, 1959.

[4] H. Smith and T. M. Sugden, "Studies on the ionization produced by metallic salts in flames. III. Ionic equilibria in hydrogen/air flames containing alkali metal salts," *Proc. Roy. Soc. London A*, vol. 211, no. 1104, pp. 31–58, 1952.

[5] M. Heron and K. Mphale, "Radio wave attenuation in bushfires, tropical cyclones and other severe atmospheric conditions," James Cook University, Final Report on EMA Project 60/2001, 2004.

[6] P. M. Attiwill and M. A. Adams, *Nutrition of Eucalypts*. : CSIRO, 1996.

[7] J. Boan, "Radio propagation in fire environments," in *Work. Applicat. Radio Sci. – WARS'06 Leura*, 2006.

[8] R. R. Rogers and W. O. J. Brown, "Radar observations of a major industrial fire," *Bull. Amer. Meteorolog. Soc.*, vol. 78, no. 5, pp. 803–814, 1997.

[9] Y. Itikawa, "Effective collision frequency of electrons in gases," *The Phys. Fluids*, vol. 16, no. 6, p. 831, 1973.

[10] C. Coleman and J. Boan, "A kirchoff integral approach to radio wave propagation in fire," presented at the IEEE Antennas Propag. Soc. Int. Symp., HI, 2007.

[11] J. Boan, "FDTD for tropospheric propagtion with strong cold plasma effects," in *IEEE Antennas Propag. Soc. Int. Symp.*, Albuquerque, 2006, p. 3905.