The Signal Propagation Effects on IEEE 802.15.4 Radio Link in Fire Environment

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***Abstract*—Radio communication systems play a major role in supporting wildfire suppression crews in firegrounds. In this paper, we consider the effect of fire upon 2.4 GHz IEEE 802.15.4 radio link and propagation characteristics variation over the distance. Observations revealed that the considered bandwidth has perceptible degradation in signal strength and link quality in the presence of fire. Moreover, consistent results were observed in deterioration in signal strength and link quality parameters over the distance for the considered small fire environment.**

***Keywords*—bushfire, fire, radio propagation, link quality, RSSI**

I. Introduction

A bushfire or a wildfire is a non-organised fire in flammable vegetation occurring in the countryside or a forest area [1]. A wildfire is different from other fires by its extensive size and the speed that it can spread out from its initial source. Moreover, it is able to vary the direction of spread unexpectedly, and it can jump over gaps such as roads, rivers and fire breaks. Bushfires are capable of having significant impacts on individuals, communities, and public and private assets. They can endanger human life and property, agricultural and forest production, animals, biodiversity, air and water quality, cultural heritage and infrastructure [2]. Black Saturday bushfires which were a series of bushfires ignited on February 2009 across the state of Vitoria in Australia is an example of such a disaster. This fire caused over 450000 ha to burn down and as a result 173 died and over 400 people were injured [3], [4]. Wildfires occur on every continent except Antarctica. The state of Victoria in Australia together with Southern California and the South of France are the worst three bushfire regions on the planet [5]. Being a large continent stretching from the tropics into cool temperate regions, Australia has wide range of climates, and a number of very extreme climate conditions. As a consequence of low annual rainfall, fire prone vegetations and frequent droughts coupled with high summer temperatures, Australia is subjected to recurring bushfires of varying intensities [5]. Throughout the year, some part of the continent is susceptible to bushfires as a result of climatic variation across Australia [2].

When the temperature of gas is so high, the electrons can overcome the atomic binding energy and if further heated, all the electrons get separated from the atoms and ultimately the gas become mixture of freely moving electrons and nuclei. This substance is called fully ionized plasma and it is often referred to as fourth state of matter [6]. Absorption in partially ionised plasma significantly effects the electromagnetic signal attenuation and dispersion. Bushfire plume consists of partially ionized gas with majority of uncharged particles and minority of charged particles. Due to the presence of these charged particles, flames considered to be conductive [7]. Ionized electrons interact with electromagnetic waves, resulting dispersion and attenuation. Experiments were carried out for further investigation of the above phenomenon, under stimulated fire conditions by adding metal salts to flames [8], [9]. Some argue that there is considerable amount of alkalis present in the fire plume to generate significant electron population in a bushfire environment to effect VHF (very high frequency) and UHF (ultra high frequency) radio signals [10].

In normal atmospheric conditions, radio waves curve slightly toward the earth surface due to the atmospheric pressure and temperature profile which cause a higher refractive index at the ground level. In a fire environment large temperature gradients and changes in the atmospheric gases severely affect the refractive index. The situation causes for subrefractive conditions that induce radio energy to bend away from the ground, resulting reduced signal strength of ground based units [9].

Observations of a smoke plume using radar measurements propose another interesting mechanism of absorption of radio wave energy [11]. Scattering by settling particles swept up by the fire contribute in absorption and redistribution of radio signal strength. The above investigation also suggests that refractivity due to heating and turbulent mixing of air and smoke plume may have lead to strong scattering of radio waves. A similar situation can be expected in an event of bushfire where surround atmosphere is covered by huge smoke plume.

In Australia, several incidents were reported in degradation of radio signals and concerns were raised by fire fighters on the reliability on radio communication in severe bushfire conditions [12], [13]. Several studies were carried out to explain the interruption in the communication between radio transceivers in these severe conditions. Early experiments performed in X-band, SHF (super high frequency) and UHF bands in hot flames observed that these electromagnetic waves significantly influenced by flames [14], [15], [16]. Recently, Mphale *et al.* [17] has conducted some experiments in VHF frequencies such as 30 MHz, 150 MHz and Boan *et al.* [9] in VHF ($160-180$ MHz) and UHF ($400-450$ MHz and $850-950$ MHz) frequency bands. In this paper, we consider the effect of small-scale fire upon IEEE 802.15.4 compliant, 2.4 GHz ISM (industrial, scientific and medical) radio band link and variation of link quality and received signal strength characteristics over the distance.

The remainder of paper is organized as follows. In Section II, we describe the signal propagation characteristics in fire environment. In Section III, we discuss the characteristics of radio nodes used in this experiment and in Section IV, we explain the experimental setup. In Section V, we include some observations and explain results. Section VI concludes the paper.

II. Propagation Characteristics of Radio Signals in Ionized Flame Medium

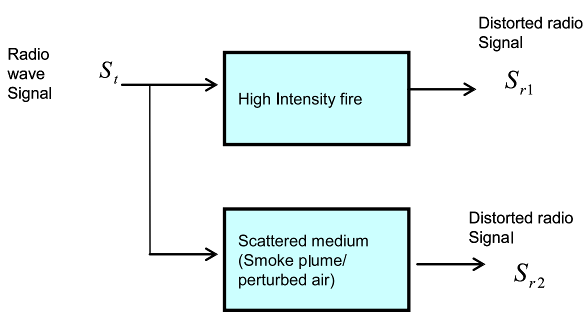

Fig. 1. Radio signal disruption in fire environment

Let, the plasma frequency is negligible compared to electron-neutral collision frequency. Then if it is assumed, flame particles have Maxwell velocity distribution, radio wave propagates through grassfire can be predicted to have attenuation and phase shift [17]. If plane polarized radio waves propagate through weakly ionized flame medium in an average path length d, while direction of propagation is positive, its amplitude E_f is given by

$$E_f(x) = E_0 exp\left\{-\int_0^d \bar{\gamma}_{eff}(x)\,dx\right\}, \tag{1}$$

[18] where E_0 is free space electric field strength and $\bar{\gamma}_{eff}$ is complex, effective propagation constant which can be written as $\bar{\gamma}_{eff} = \alpha_f + i\beta_f$ [19], where α_f is the attenuation coefficient and β_f is the phase shift coefficient.

Coal gas air flame in temperature 2200 K, two properties collision frequency and electron density for X-band microwave frequencies have been determined as 8.8×10^{10} s^{-1} and 2.0×10^{17} m^{-3} respectively [15]. A similar experiment has been carried out to determine the above two parameters in pure jet flames (temperature up to 1290 K) at VHF and it was observed two parameters as 6.5×10^{8} s^{-1} and 1.9×10^{12} m^{-3} respectively [20]. These two results have been used in simulating attenuation and phase coefficients for microwaves in forest fuel flame, determining that the two parameters are in between the coal gas air and pure jet flames. For collision frequency 1.1×10^{10} s^{-1} and electron densities in the range of $1-3.2\times10^{16}$ m^{-3} attenuation is observed in the range $0.8-4.2$ dB whilst phase shift varies from $6-34$ degrees [17].

III. Link Behavior of Radio Transceivers

The Imote2 radio nodes which were utilized in our experiment, integrate 802.15.4 radio transceivers from ChipCon (CC2420) for wireless communication. The CC2420 facilitates 250 kb/s data rate along with 16 frequency channels within the 2.4 GHz ISM band [21].

A. Received Signal Strength

Devices in IEEE 802.15.4 standards designed to use receiver energy detection as a part of channel selection algorithm. Channel selection decision is made by the network layer. The receiver energy is an estimation of the signal power received from a particular frequency channel defined in IEEE standard [22]. For CC2420 estimation of received signal strength can be directly read from built-in RSSI (Received Signal Strength Indication) provider which produces a digital 8 bit value. IEEE 802.15.4 recommends to have energy detection over 8 symbol period and CC2420 determines RSSI value over $128\,\mu$s which is equivalent to the recommended symbol period [23].

B. Link Quality

The link quality indication (LQI) measurement is a characterisation of the strength and/or quality of a received packet. Different parameters such as RSSI value, signal-to-noise ratio estimation or combination of these can be employed to estimate the LQI measurement. Based on the IEEE standard, LQI value to be limited to the range 0 through 255 and MAC software is responsible for converting appropriate scaling for the LQI value [22]. Considering the disadvantage of using RSSI value directly to calculate LQI value, CC2420 make use of additional parameter, average correlation value $(CORR)$ to determine the link quality. This value can be considered as a measurement of chip error rate. Maximum quality frame is indicated by a correlation value of ~ 110 while a value of ~ 50 is typically the lowest quality frame identified by CC2420. The MAC software converts this value to the range $0-255$ by $LQI = (CORR - a).b$, where a and b are empirically determined based on packet error rate measurements [23].

IV. Experiment Setup

In this pilot experiment, LP gas was used as the fuel and small fire of radius 10 cm was ignited in-between the propagation path of Imotes2 nodes. One node was kept in a fixed distance of 0.2 m away from the fire column and received signal strength and link quality measurements were

TABLE I
AVERAGED LINK QUALITY AND RECEIVED SIGNAL STRENGTH MEASUREMENTS

Distance (m)	RSSI Measurements (dBm)			Link Quality Measurements		
	Fire Height h = 10 cm	Fire Height h = 5 cm	Without Fire	Fire Height h = 10 cm	Fire Height h = 5 cm	Without Fire
0.2	-57.24	-55.08	-55.00	104.35	104.45	104.58
0.4	-59.63	-57.91	-56.49	104.40	104.41	104.46
0.6	-62.12	-62.07	-61.95	104.27	104.33	104.43
0.8	-64.52	-64.00	-63.84	104.30	104.34	104.41
1	-64.78	-64.48	-64.00	104.15	104.24	104.31
1.2	-69.64	-68.96	-68.04	104.11	104.17	104.30
1.4	-69.69	-69.39	-68.73	104.09	104.14	104.27
1.6	-70.03	-69.47	-68.87	104.03	104.07	104.15
1.8	-73.15	-73.13	-72.46	103.90	103.96	104.08
2	-75.13	-73.30	-72.55	103.85	103.90	103.94

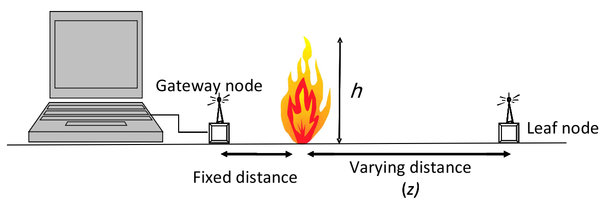

Fig. 2. Experimental setup. Measurements of radio link parameters were taken varying the distance (z) from leaf node to the fire column.

taken varying the distance (z) of other node with respect to fire column as shown in Fig. 2. Nodes were programmed using NetC programming language under TinyOS 1.x development environment. Node that kept in the fixed distance was configured as the gateway node and the other as the leaf node. Gateway node determines the link quality and the received signal strength form packet received by the leaf node and write these values into file internal to the node. Subsequently, these data are transferred to the PC using BluSH shell program which is a user interface to the Imote2. This transferring mechanism executed each time after running the experiment. For each fire height, 30 RSSI and LQI measurements were recorded in each distance. Measurements were taken in three sets for each distance, once without fire and other instances with fire heights (h) 5 cm and 10 cm.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

In a real fire situation, a portable radio carried by a firefighter who operates closer to the fire is equivalent to the gateway node in the experiment. The leaf node in the test is corresponding to the central communication point or incident commander (IC) in a fireground. This central communication point is relatively stationary with respect to the other radio devices in a fire suppression situation. However, in our experiment we obtain measurements while moving the leaf node. Nevertheless, ultimate results would not be affected even if we moved the gateway node while keeping the leaf node in a fixed distance. Therefore, the experiment setup is comparable with firefighter communication setup in a real fireground.

The Imote2 nodes which were specially programmed for

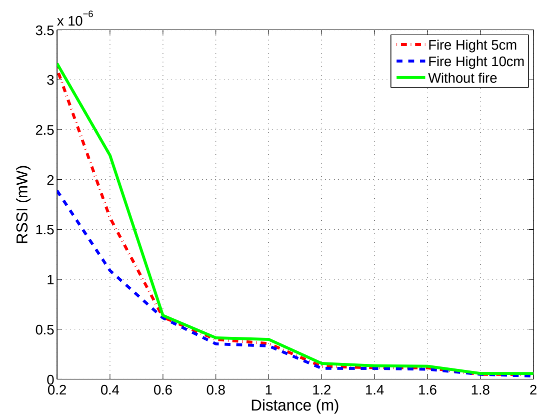

Fig. 3. The variation of received signal strength over the distance. Influence of fire is much significant while nodes are closer and the effect of distance dominates around 0.6 m separation.

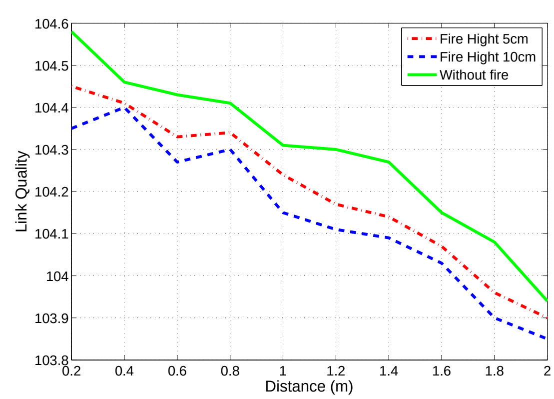

Fig. 4. The variation of link quality over the distance. Clearly, the presence of fire deteriorates the link quality of the radio link. The significance of the effect further depends on the dimensions of the fire.

the above experiment have higher signal extinction over short distance. Preceding observations verified complete isolation of nodes while they were apart by 7 m distance. This functionality was assumed to be an advantage in following distinguishable measurements in the small fire environment when compared to fire excluded environment.

RSSI and link quality values have clear difference while the fire column exists than its absence. These measurements tend to have lower values in the presence of fire and consistent results were observed over the distance. The difference is much significant in received signal when nodes are closer to fire while extinction over the distance dominates around 0.6 m separation. This is due to the small dimensions of fire that we used in this experiment. In contrast, under bush fire circumstances this distance will be extensively large as a result of substantial size of the fire plume. Further, link quality value pattern does not follow the exact RSSI value pattern. The decision made by the node on LQI value depends on the MAC layer software algorithm explained in the Section III. This confirms that value of link quality does not solely depend on RSSI value.

Received signal strength tends to degrade exponentially as indicated in (1). However, it is difficult to compare the results entirely with the theoretical prediction, without measuring parameters such as election density of the fire column. A complex experimental mechanism is required to determine the election density in fire column and it is beyond the scope of this pilot experiment.

VI. Conclusion

The pilot experiment discussed in this paper shows that fire has significant effect over considered 2.4 GHz ISM bandwidth. It is revealed that the signal strength and link quality parameters are further dependent on the dimensions of the fire column and performance of link could severely impact under extreme fire conditions such as bushfires. Further investigations and experiments are supposed to be conducted to improve the understanding of the propagation effects on radio signals under fire environment.

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