Impact of Bushfire Dynamics on the Performance of MANETs

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***Abstract*—In emergency situations like recent Australian bushfires, it is crucial for civilians and firefighters to receive critical information such as escape routes and safe sheltering points with guarantees on information quality attributes. Mobile Ad-hoc Networks (MANETs) can provide communications in bushfire when fixed infrastructure is destroyed and not available. Current MANET solutions, however, are mostly tested under static bushfire scenario. In this work, we investigate the impact of a realistic dynamic bushfire in a dry eucalypt forest with a shrubby understory, on the performance of data delivery solutions in a MANET. Simulation results show a significant degradation in the performance of state-of-the-art MANET quality of information solution. Other than frequent source handovers and reduced user usability, packet arrival latency increases by more than double in the 1st quartile with a median drop of 74.5 % in the overall packet delivery ratio. It is therefore crucial for MANET solutions to be thoroughly evaluated under realistic dynamic bushfire scenarios.**

***Index Terms*—QoI, MANETs, Bushfire Communications**

I. Introduction

Recent Australian bushfires caused serious social and economic damage. Maintaining functional communication network during bushfires is crucial for saving lives and properties. Rapidly moving bushfires destroy telecommunication infrastructure, making Mobile Ad-hoc Network (MANET) a potential solution for emergency communications. For instance, a recent ad-hoc network used goTenna [1] technology to establish communication among a group of campers. In bushfires, however, the requirements of safety information vary with time and locations of users. For example, the information of safe shelter places must be timely delivered to affected residents with precise location data to avoid casualties.

Recent MANET data forwarding solutions have shifted from low-level network metrics towards meeting information needs of querying nodes [2]. The state-of-the-art method to rank sources according to information requirement criteria is to use Quality of Information (QoI) [3]. A recently proposed method tailors QoI with Thresholds (QoIT) [4] when specific needs of querying nodes are known. QoIT is based on a measure of "goodness" i.e., the closeness of information from a source and its down-link path in meeting the demands of a querying node. QoIT improves performance of QoI, however, so far it is tested only under static bushfire scenarios wherein real-world it is rare for bushfire to remain static in an area. For example, the recurring Australian bushfires have demonstrated mobility patterns that severely impacted efforts to restore and maintain communications [5].

This paper is an initial study to understand the impact of dynamic bushfire on QoIT performance in MANETs. In this study, we extend the simulator in [4] with a realistic field-based dynamic bushfire model [6] and run QoIT in static and dynamic bushfire scenarios while keeping the simulation parameters the same. Bushfire spread endangers multiple nodes, further partitioning the MANET into disconnected clusters, leading to a significant drop in QoIT performance. We quantify the degradation in terms of user usability (percentage of users whose all quality needs are completely met), source handover frequency, packet latency and its delivery ratio. With dynamic bushfire, source handover frequency overhead increases 4 times and user usability drops by 40.25 %. In terms of packet transmission, not only its delay increases by 66.1 % in the 1st quartile but also the delivery ratio drops by 74.5 % in median.

II. Related Work

A MANET is an infrastructure-less decentralized network, where nodes forward data for other nodes. Paths between end nodes are dynamic as nodes join and leave the network. To forward data intelligently, Quality of Service (QoS) based routing in ad-hoc networks [7] selects paths that fulfill one or more QoS need(s). These include metrics at physical, MAC, and network layers, but do not consider the role of the lower layer metrics towards user satisfaction at the application layer. Recent applications of software-defined networking to improve network layer performance in MANETs are shown in [8].

Quality of Information (QoI) [2] evaluates the impact of network-level QoS attributes on application layer information features to determine source node and downlink path for data forwarding to the querying node. Application layer features depend upon operational context, for example, in bushfire scenario information freshness and correctness are the required QoI features. Comparison of QoS and QoI based routing in MANET [9] shows that the former performs better for tasks with single QoS need, whereas the latter outperforms with multiple QoS needs. Analytic hierarchy process is used in QoI-aware networking (QoI-AHP) [3] to select data delivery path. QoI-AHP does not consider user needs as its decision is based

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on an overall QoI score [9]. QoI with Thresholds (QoIT) [4], a recent QoI study, makes source or path selection decision by exploiting user-specified thresholds of network metrics to meet application layer quality requirements of the user. Tested under static bushfire, QoIT improves network performance regarding user usability, source bottleneck, and computation overhead, in comparison to QoI-AHP.

In real-world, fire spreads with time e.g., recent Australian bushfires damaged a vast area of land. MANETs face challenges in dynamic bushfires as it interferes with signal quality, damages communication nodes, and limits the mobility of users. Despite these issues, there has been little research on the impact of bushfire dynamics on MANET performance [10].

Fire behavior models are fuel-type specific with various models developed to predict the spread rate, direction, and height of the fire. Fire spread prediction models [11], [12] include physical and empirical models. The physical model precludes real-time forecasts due to its high computation time, making its application limited within a certain area range [11]. The empirical model is suitable for operational use due to its computational simplicity. It uses statistical analysis to illustrate fire behavior and analytical functions to relate dependent variables to independent variables [12].

Empirical models are widely used to predict the fire spread rate. These include fire behavior tables incorporated in Forest Fire Danger Meter (FFDM) [13] and Forest Fire Behaviour Tables (FFBT) [14]. Both are developed using experimental fires in dry eucalypt forest fuels. Impact of fuel characteristics on fire spread show that near-surface fuel, fuel moisture content, fuel quantity, and its arrangement and structure should be considered to predict fire behavior. A recent survey of empirical models for various Australian fuel types [12] suggests that the model in [6] is suitable for dry eucalypt forest with a shrubby understory to predict the fire spread rate. The model predicts fire spread rate beyond the range of experimental data and is tested against fire spread observations of experimental fires and wildfires in dry eucalypt forests in Southern Australia [6].

Impact of these realistic fire behavior models on QoI performance in MANETs is not well understood. We address this issue by studying the impact of dynamic bushfires on QoIT performance in this paper.

III. QoIT and Bushfire Models

To study the impact of dynamic bushfire on MANETs, we use QoIT source selection approach in [4] for information transfer to users, and fire model in [6] for bushfire mobility.

A. QoIT Model

QoIT source selection process uses fine-grained details regarding the ability of each source, and the path from it to querying node, in meeting an application's quality needs. It defines the threshold for network metrics to depict the required level of performance in meeting an application's information quality needs. QoIT works by (i) computing the goodness measure of each network metric, indicating how well a network metric can meet user's demand, next (ii) using goodness measure values, QoIT computes quality metric scores, and (iii) based on quality metric scores, it then computes the number, priority, and percentage of quality needs of a querying node that a source can meet. The last step leads to the source selection decision. For details of the source selection process of QoIT, the interested reader is referred to [4].

B. Fire Model

For dry eucalypt forest with shrubby understory, an empirical model is developed [6] using Project Vesta experimental fires data [15] to predict field-based fire spread rate beyond the range of experimental data. To study the impact of dynamic bushfire on MANET, it is necessary to specify a potential fire spread rate (R_p). R_p needs following attributes values as input:

- *Fuel Moisture Content (M_f):* It is the amount of water in fuel, expressed as a percent of the dry weight of fuel. M_f determines fuel's fire ignition potential and the rate of fire spread. M_f depends on environmental conditions and fuel characteristics. With decreasing M_f, the fire ignition increases. Totally dry fuel has $M_f = 0\,\%$. Fuel with $M_f < 30\,\%$ is considered dead [6], whereas the moisture content of such fuel is controlled exclusively by environmental conditions and is critical in determining fire potential.
- *Slope (θ):* The slope has a major influence on bushfire spread and causes heat transfer from the flame to fuel ahead of it i.e., fire size increases with increasing slope. Compared to flat terrain, fire spread rate can increase by two times on 10° slope and 4 times on 20° slope [13]. Minimum spread rates occur at slopes of –16°, that increases roughly linearly between –16° to +16° and accelerates at 16° to 25°. For $\theta > 25°$ fire spread increases linearly but in much greater proportion to the slope [16]. The impact of slope is low in absence of wind.
- *Wind Speed (U):* Fire spread rate also changes with wind speed [6], and under certain conditions can be explained largely by wind speed alone. For example, for consistent fire spread in grasslands of Australia in natural pastures on level ground, wind speed at 10 meters height should exceed 5 $km\,h^{-1}$ [17]. Forward spread rate in fires burning dry eucalypt forests and temperate shrub-lands is roughly 10% of the average 10 meters open wind speed [18].
- *Fuel Hazard Scores (FHS):* It indicates the level of danger associated with the fuel regarding its inflammability and represents fuel attributes (F_i) i.e., fuel structure, arrangement, continuity, and live–to-dead ratio. FHS is used for fuel assessment since it is rapid and easily implemented, and relates to difficulty of fire suppression and behavior.

The model assumes that the predicted fire spread rate, R_p (1), has quasi-steady speed in $km\,h^{-1}$. U_{10} is mean wind speed at 10 meters height in open between 7.3 - 25.9 $km\,h^{-1}$, F_i are fuel attributes, M_f is dead fuel moisture content (%), θ is the slope in degrees, and $\Phi_i(.)$ is the function of wind speed, fuel, moisture content, and slope respectively.

$$R_p = \Phi_1(U_{10})\Phi_2(F_1,\ F_2,\ \dots,\ F_n)\Phi_3(M_f)\Phi_4(\theta) \quad (1)$$

Fuel moisture function $\Phi_3(M_f)$ in (2), depends on the relationship of fuel moisture content and spread rate of Jarrah forest fuels. The relationship is developed from data of dry summer burning conditions with surface fuel moisture content (M_{fs}) in 5.6% - 9.6% range [6], assuming no wind effects.

$$\Phi_3(M_f) = 18.35 M_{fs}^{-1.495} \tag{2}$$

With increasing slope, flames contact with fuel gets closer that ignites the fuel and increases fire spread rate. The exponential function $\Phi_4(\theta)$ in (3) for $\theta \geq 0°$ is adopted, as it is consistent with slope functions applied to other fire models. The study in [6] assumes the slope to be in 0° - 30° range.

$$\Phi_4(\theta) = exp(0.069\theta) \tag{3}$$

For experimental fires the adjusted fire spread rate, R_A, equivalent to $\Phi_1(U_{10})\Phi_2(F_1, F_2, \ldots, F_n)$, is modelled in (4). Here θ = 0° and M_f is constant, so as to base the fire spread adjustment only on wind speed and fuel hazard score variables.

$$R_A = R_t + 1.5308(U_{10} - U_t)^{b_1} \cdot FHS_s^{b_2} \cdot (FHS_{ns} \cdot H_{ns})^{b_3} \cdot B_1 \tag{4}$$

where, R_t = 0.03 kmh^{-1} is threshold spread rate at threshold wind speed U_t = 5 kmh^{-1} at 7% M_{fs} and θ = 0°, FHS_s is surface fuel hazard score (1.3 - 3.9), FHS_{ns} is near-surface fuel hazard score (0.2 - 3.8), H_{ns} is near-surface fuel height (5 - 30 cm), b_1 = 0.857, b_2 = 0.930, b_3 = 0.636 are regression constants regarding R_A, and B_1 = 1.03 is the bias calculated as ratio of observed mean to the mean of predicted values [6].

Final model is generated by incorporating R_A, $\Phi_3(M_f)$, and $\Phi_4(\theta)$ into (1), to predict the potential fire spread rate (R_p).

IV. Evaluation and Analysis

A. Simulation Setup

To evaluate QoIT performance in MANET under a realistic dynamic bushfire, we integrate the fire behavior model [6] in (1) into simulation environment built with JAVA APIs [4][1]. The simulator already has QoIT support which decides source nodes and network paths based on the requirements of the querying nodes. QoIT source selection process polls in real-time the required network metrics from the simulator. Below we discuss the simulated network in terms of features used at different layers and the application of the fire behavior model.

1) Physical Layer: We use standard log-distance path loss model under dense foliage to calculate radio attenuation and data rate. Network connectivity on a link between nodes exists if its capacity $> 0\,Mbps$. SNR generated using (5) is used to calculate link data rate according to Shannon's capacity, where T_p is radio transmission power of 20 dBm, f is carrier frequency within 2.4 GHz band, d is Euclidean distance between end nodes in km, r is random fading between 0 - 1 dB, and n_{cutoff} is Nyquist noise cutoff level with -180 dBm. For simplicity, we do not consider fire's impact on signal strength.

$$SNR = T_p - 32.45 - 4(10log_{10}(f * d)) - r - n_{cutoff} \tag{5}$$

[1]https://github.com/AmeerShakaybArsalaan87/QoIT_under_DynamicBushfire.git

2) Data-Link Layer: We use a time division multiple access method called Node Activation Multiple Access (NAMA) based slot reservation scheme for bandwidth allocation, where resources are reserved immediately after source selection as in [4].

3) Network Layer: Dijkstra's algorithm is used to establish the shortest paths to route users and control traffic. Path weight is sum of link weights, whereas link weight is inverse of link's data rate. The shortest path is the one with smallest weight. In dynamic scenario, distance and random fading between nodes are evaluated to decide a link's set-up, breakage, and data rate.

4) Application Layer: All traffic is assumed to go from a source to querying nodes. Since the goal is to provide users with what they need, we do not model any specific application data-type, rather synthesize differences in desired features of queried data by defining minimum needs of network metrics. Querying nodes query the sources simultaneously to select an information source. We use the same QoIT settings as in [4].

5) Fire Spread Model: At the start of the simulation, fire is ignited at 15 - 20 random locations in the simulated area. To imitate continuity or variation in topography, environment and fuel bed information, the variable values of fire spread behavior model vary with fire locations. The ranges of fire spread influencing variables are given in Section III-B.

Fire spreads using (1) from the ignition point or line of fire in wind direction, at the rate of 0.04608 - 12.1824 kmh^{-1}. The range of fire spread rate, R_p, is calculated using the minimum and maximum values of the influencing variables. Each simulation run executes until all data packets are delivered and/or expired. The changes in simulation scenarios occur every second and so does the variation in bushfire spread. Fire spread beyond the simulation area is considered vanished.

Network paths are established at the start of the simulation. Nodes that come in close contact with the line of fire are considered dead and excluded instantly from the network for the rest of the simulation. Dead node leads to re-establishment of new network paths. If the dead node is a selected source or an intermediate node, the decision is made by QoIT regarding the best available source or path at the time, that might result in source handover. Since all nodes are considered to be placed on the ground level, flame height is excluded in the simulation.

QoIT selects a source for a querying node using existing network information. When a source is assigned to a querying node, the number of packets (to be delivered to querying node) are randomly chosen between 10 - 15. Each packet is of 1500 *bytes* with TTL of 20 - 60 *seconds*. The number of packets delivered, before the selected source or an intermediate node along the path disconnects, makes the querying node to receive the remaining packets from the newly selected source or path.

B. Results

We simulate a bushfire field of 20 km^2 in area. There are 60 static nodes (all acting as relays) with 10 source, 10 querying, and the rest as intermediate nodes. We run 20 experiments, each having two scenarios based on fire spread models i.e., static and dynamic. In each run, nodes are

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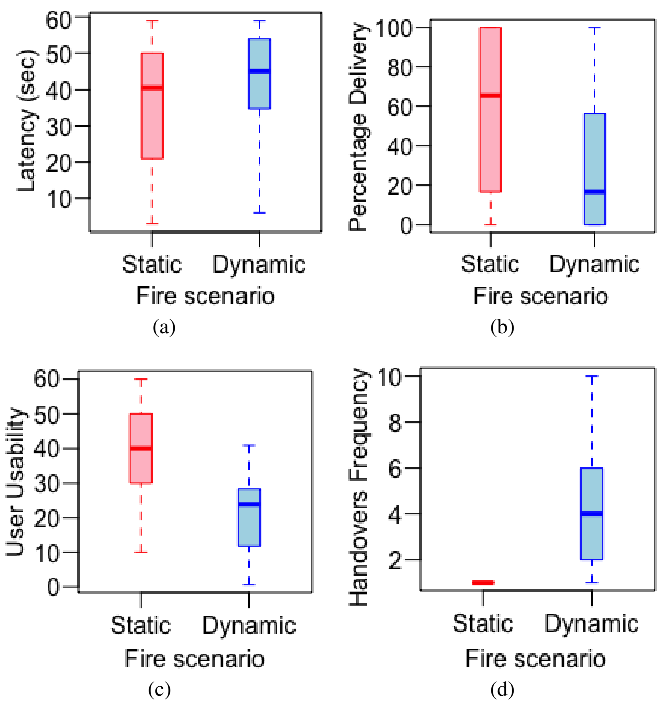

Fig. 1: (a) Packet latency, (b) percentage delivery, (c) user usability, and (d) source handover frequency, under static and dynamic bushfire scenarios.

positioned randomly. To evaluate the bushfire effect, we keep all of the simulation parameters the same for both scenarios, other than fire dynamics.

1) Packet Latency and Delivery Ratio: Two metrics commonly used to assess a network's performance are (i) *delivery ratio*, which measures the number of successfully transmitted packets to total number of transmitted packets and (ii) *latency*, a measure of delay faced by packets in arriving at a destination.

Fig. 1a shows that with dynamic bushfire, latency increases by 12.5 % in the median and by 66.1 % in the first quartile, which is significant especially when messages do not arrive in-time for emergency services. The situation worsens when messages do not arrive at all, which can be seen from Fig. 1b. Here with dynamic bushfire, the message loss increases up to 74.5 % by the median. This simple test points out that network performance worsens at the time when they are most needed to save lives. It is, therefore, necessary to devise alternate ways to cope with the partitions in the network. Note, the performance difference of the two scenarios is similar when the fire does not overlap the nodes and links in the network.

2) User Usability: We study QoIT performance in terms of user usability i.e., the number of users whose all quality needs are met by sources. Dynamic bushfire scenario significantly drops user usability, as shown in Fig. 1c. The drop is by 40.25 % in the median, which again points to dying out of nodes and loss of the links towards optimal source nodes.

3) Source Handover Frequency: We examine the overhead of re-running QoIT to choose new sources for querying nodes that have lost their previous connections due to bushfire spread. Fig. 1d shows source handover frequency to increase from 1 to 4 in median cases and maximum up-to 10 times.

V. Conclusion

In emergency situations, it is important to receive critical information with guarantees on information quality attributes. MANETs provide communications in bushfire with guarantees on delivering information with minimal needs, by using state-of-the-art QoIT scheme. However, QoIT is tested only under static bushfires. In this work, we assess the performance degradation caused by a dynamic bushfire in QoIT-based communication in MANET. Results show significant degradation regarding source handover frequency, user usability, packet latency, and delivery ratio, due to network dis-connectivity caused by spreading bushfire. In future work, we aim to deploy Unmanned Air Vehicles (UAVs) in dynamic bushfires, to minimize network partitioning and improve network performance.

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