Interference Avoidance in Rapidly Deployed Wireless Ad hoc Incident Area Networks

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Abstract— In [1], we investigated the use of multi-hop relays (a.k.a. breadcrumbs) to extend the range of public safety communications in indoor environments where the radio propagation conditions are harsh or wireless communications are limited by distance. In this work, we consider the impact of interference on the reliability of the breadcrumb system. We develop a simulation model for the system that considers the incident area floor plan, the characteristics of radio propagation within the incident area, emergency responders' mobility, and the distributed functionalities of the breadcrumb system. We then evaluate the performance of the breadcrumb system in the presence of interference showing that it is diminished. Consequently, we consider the use of the cognitive radio technology to enable breadcrumbs to detect interference, to identify vacant channels, and to dynamically and autonomously adapt their channel selection to enhance the system performance. We develop the functionalities of cognitive radio in our simulation, re-evaluate the system performance in the presence of interference, and show that employing cognitive radios alleviates the impact of interference. We also highlight the overhead that the cognitive radio functionalities may have under favorable network conditions.

Keywords: Mission Critical Networks, Cognitive Radio

I. INTRODUCTION

A typical Incident Area Network (IAN [2]) deployed in indoor emergency scenarios consists of emergency responders within the incident area and an Incident Command Center (ICC) safely located outside of the incident area. In such scenarios, these entities need to form a network in order to communicate. Currently, emergency responders are equipped with radios that enable them to communicate with the ICC using voice. In the future, emergency responder communication systems will support additional services such as location information, sensor readings (e.g., vital life/health signs, toxic gas, and temperature sensor readings), and video feeds from within the incident area. The ICC uses this information to command and control the operation.

Typically, little or nothing is known *a priori* about the communication environment within the incident area (e.g., radio propagation conditions and interference). If the communication environment is inadequate, communication between the emergency responders and the ICC may be compromised, affecting the ability of the ICC to command and control the operation and to account for the safety of the emergency responders. We have demonstrated in our previous work the use of multihop relays to extend the range of public safety communications in indoor environments where the radio propagation conditions are harsh or wireless communications are limited by distance [1]. Relays, which we refer to as "breadcrumbs", are deployed by emergency responders on a need-to basis repeating transmissions between emergency responders and the ICC. We proposed a deployment procedure that employs real-time link measurements and takes into account the physical layer characteristics of a mobile multipath fading environment and the radios in use. We built a prototype breadcrumb system and demonstrated its effectiveness. The idea of using relays (i.e., breadcrumbs) to extend communication range of ad hoc networks has also been proposed in general in [3, 4] and for public safety communication in particular in [5]. However, these systems require pre-deployment. A real-time deployment mechanism is proposed in [6] that considers collaboration among emergency responders to avoid redundancy in deployments of relays.

In this paper, we address the issue of interference and its impact on the breadcrumb system. Consider for instance that breadcrumbs are configured to operate on some *channel A*. If the breadcrumb system is then deployed in an environment where *channel A* is already in use by other network(s), reliable communication between the emergency responders and the ICC may be compromised due to interference from the other network(s) and increased contention for medium access.

To assess the impact of interference on the breadcrumb system, we develop a simulation model of the system in ns-2 [7]. The simulation model considers the incident area floor plan, the radio propagation characteristics of the incident area, the mobility of emergency responders, as well as the distributed functionalities of the breadcrumb system. We then use the simulator to show that interference impacts the system performance (and hence, its reliability) as it reduces network throughput, increases the number of deployed breadcrumbs, and consequently increases end-to-end delay. We then consider the use of the cognitive radio technology to alleviate the impact of interference on the breadcrumb system. We consider the case where a cognitive radio module exists at each breadcrumb allowing it to sense a set of utilizable spectrum bands within its locality, detect any activity on each, and make autonomous decisions as to which spectrum band to use in order to minimize interference. We re-evaluate the reliability of the breadcrumb system and show how the use of cognitive radio technology can alleviate the harmful impact of interference on the system.

Our contribution in this paper is threefold. Firstly, we develop a simulator that models different aspects of emergency responder communication in indoor environments including the

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operating environment, emergency responder mobility, and operations of the breadcrumb system. Secondly, we show that interference from outside sources negatively impacts the performance of emergency responder communication systems. Thirdly, we show that the cognitive radio technology can be utilized to enhance the resilience of emergency responder communication systems to outside interference sources.

This paper is organized as follows. In Section 2, we summarize the functionalities of the breadcrumb system. In Section 3, we discuss the components of the simulation model we developed for the breadcrumb system. In Section 4, we evaluate the performance of the system in the presence of outside interference sources. We discuss in Section 5 how the utilization of the cognitive radio technology can enhance the resilience of the breadcrumb system to interference. We conclude and discuss future work in Section 6.

II. BREADCRUMB SYSTEM

The breadcrumb system is a rapidly deployable ad hoc network that is used in indoor emergency situations to facilitate reliable communication between emergency responders and the ICC. Emergency responders drop the breadcrumbs within the incident area as needed to facilitate their communication with the ICC. We focused in [1] on the deployment strategy for breadcrumbs. We developed a strategy whereby the decision to drop a new breadcrumb depends on the quality of the links from the emergency responder to the breadcrumbs already deployed. This adaptive strategy allows the system to operate across a variety of scenarios. The link quality metric we use is RSS (Received Signal Strength), which we've shown to be an effective metric. Channel probing signals are used to calculate the RSS. The radio of each emergency responder periodically broadcasts small channel probes (every Δ seconds). Upon successful receipt of a probe, a deployed breadcrumb or the ICC replies with a probe ACK (acknowledgement). The emergency responder records the RSS of each probe ACK received on each link. For each missing probe ACK on a given link, a low level default value of S_0 is used, where S_0 is less than the receiver sensitivity of the radio. Emergency responder radios keep a running average of the last N RSS values recorded for each link and consider that to be a measurement of the quality of this link. An emergency responder decides to drop a breadcrumb when the highest running average RSS of all links is below some threshold S_{th}. Table I shows the parameters used by the system.

We demonstrated the effectiveness of the breadcrumb system using a prototype that we built using 900 MHz TinyOS Crossbow MICA2 Motes[1]. In our prototype, the emergency responders exchange text messages with the ICC and send one-way sensor readings (the emergency responder is equipped with light and temperature sensors) and RFID (Radio-Frequency Identification) assisted location information.

While the advantage of the lower frequency 900 MHz system is better signal penetration through obstacles, we wished to test streaming applications such as two-way voice and video which the limited bandwidth and processing power of the motes did not permit. Therefore, we developed an analogous prototype system using 2.4 GHz IEEE 802.11b/g radios operating in the ad hoc mode. The deployment protocol of the 2.4 GHz system is very similar to that of the 900 MHz prototype.

TABLE I. PARAMETERS OF THE DEPLOYMENT STRATEGY

Parameter	Description	Value
Δ	Mobile probe period	0.025 s
N	RSS Avg. filter length	10 readings
S_0	Default RSS value	-84 dBm
S_{th}	Deployment threshold	-60 dBm

III. BREADCRUMB SYSTEM SIMULATION MODEL

In this section, we discuss the components of the simulation model we developed for the breadcrumb system. There are three components considered: the characteristics of the incident area, the mobility of emergency responders, and the functionalities of the breadcrumb system.

A. *Characteristics of the Incident Area*

In order to correctly represent the operation of emergency responders and the breadcrumb system in indoor emergency scenarios, the characteristics of the incident area need to be taken into consideration. This includes the incident area floor plan (which we'll later use to define how emergency responders move within the incident area) as well as radio propagation characteristics. We used [8] to define a module within ns-2 that considers the floor plan of the area where a network is deployed by defining the following components:

- Domains: A domain is defined as an area where nodes can move freely within its boundaries. This can represent a room within a building. The boundaries of each domain are defined as well as its entry/exit point. Nodes can only enter/exit a domain through its entry/exit point.
- Domain Connectors: A domain connector interconnects different domains. This can represent corridors that interconnect rooms within the same floor or stairwells that interconnect different floors. For a node to move from one domain to another it must first exit the domain from its exit point, move along the domain connector towards the destination domain, and enter the destination domain through its entry point.

Figure 1 shows the floor plan of the 2nd floor of an office building used in [1].

The radio propagation characteristics of the incident area are also another issue that is of concern to our system. This dictates the quality of communications between emergency responders and the ICC, which in turn affects the deployment of breadcrumbs. Since we are concerned with indoor network environments, we utilize the shadowing propagation model. We extend its functionalities to consider the location of a receiver relative to the transmitter (given the floor plan we developed) in assessing the attenuation to the signal at the receiver.

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[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

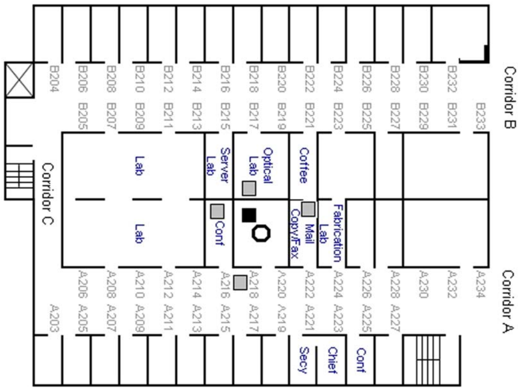

Figure 1. Model of the floor plan of an office building. Also shown are the path loss exponents used by the enhanced shadowing propagation model. A square represents a receiver and a circle represents a transmitter. Receivers represented by a black square are within line-of-sight of the transmitter (use β_1). Receivers represented by a grey square are separated from the transmitter by one domain (use β_2). Receivers in any other location use β_3.

The overall shadowing model is represented as $\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta\log\left(\frac{d}{d_0}\right)+X_{dB}$, where d is the distance between the transmitter and the receiver, d_0 is a close-in distance that is used as a reference, β is a path loss exponent that is specific to the communication environment, and X_{dB} is a Gaussian random variable that represents the environment's shadowing deviation [7]. One of the limitations of the current shadowing model implementation in ns-2 is that a single average value for the path loss exponent is assumed for a simulation environment. In a mobile network environment, however, the path loss exponent changes based on the locations of the transmitter and the receiver (e.g., line-of-sight vs. non line-of-sight). We used the floor plan we defined to modify the shadowing propagation model so as to consider the relative location of the receiver with respect to the transmitter when the received signal strength is calculated. Three different values of path loss exponent, β_1, β_2, and β_3, are utilized based on experiments conducted in [9] to describe the characteristics of radio propagation in indoor environments. The first path loss exponent value β_1 is used when the transmitter and the receiver are within line-of-sight. When the transmitter and the receiver are not within line-of-sight two cases are considered based on the number of physical barriers between them (e.g., walls, doors, etc.). If a single physical barrier stands between the transmitter and the receiver, a path loss exponent $\beta_2 > \beta_1$ is used. If more than one physical barrier stands between them, a path loss exponent $\beta_3 > \beta_2$ is used. The three values can be estimated based on measurements pre-conducted within the network environment, for example, or based on knowledge of the building structure (e.g., steel, cement, dry wall interiors). Figure 1 shows where the three path exponents apply when the transmitter is in room A218, denoted by the differently shaded receivers.

To compare the operation of the enhanced shadowing propagation model against the basic one, we conducted a simulation considering the floor plan in Figure 1 where we placed a receiver in room A218 and used a transmitter that moves from room A218 to room A222, from room A222 to room A224, from room A224 back to room A222, and finally back to room A218 from room A222. We recorded the RSS of all packets received at the receiver in room A218.

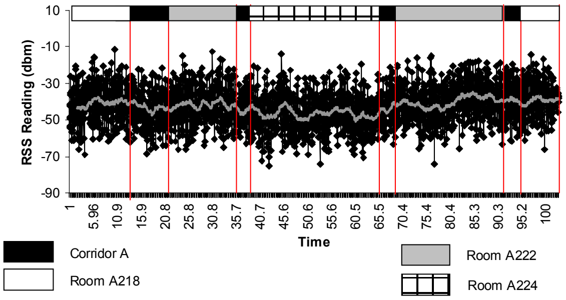

Figure 2. Basic shadowing propagation model using $\beta = 2.0$ (similar trend was observed using $\beta = 3.0$ and $\beta = 4.0$)

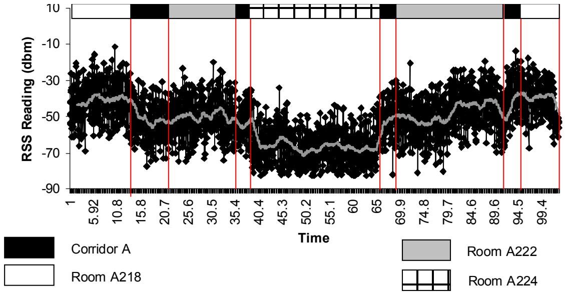

Figure 3. Enhanced shadowing propagation model using $\beta_1 = 2.0, \beta_2 = 3.0, \beta_3 = 4.0$

In the simulation, the enhanced shadowing propagation model uses $\beta_1 = 2.0, \beta_2 = 3.0, \beta_3 = 4.0$. The enhanced model is compared with the basic model in which only a single path loss exponent is used. Our simulations show that, when using the basic propagation model, the RSS reading is mostly affected by the distance between the transmitter and the receiver irrespective of the physical barriers between them (Figure 2). On the other hand, the enhanced shadowing propagation model shows increased deterioration in the RSS readings when the transmitter moves from within line-of-sight of the receiver and as the number of physical barriers between them increases (Figure 3). We find our enhanced shadowing propagation model to be more realistic than the basic model.

B. *Mobility of Emergency Responders*

In an indoor emergency scenario, emergency responder mobility is characterized by:

- *Mobility is constrained by the structure of the incident area.* A mobility scenario that considers an emergency responder to move from room A223 to room B208 must have the emergency responder first exit room A223, move west on corridor A, north on corridor C, east on corridor B, and then enter room B208. This suggests that mobility within the incident area is not entirely random and that models such as Random Waypoint and Random Walk commonly used in simulations of mobile ad hoc networks are not applicable [10].

- *Mobility pattern could be individual mobility as well as group mobility.* An emergency responder may move independently or may move within a group.
- *Mobility could be mission-oriented or random.* A mission-oriented mobility mode may represent cases when the source of a fire in an indoor emergency is identified by the ICC and all emergency responders are directed towards that source. In these cases, mobility is restricted to a path between the fire source within the incident area and the outside of the building.

We have developed a model based on [8] and the Random Trip (RT) mobility model introduced in [11] that satisfies the above requirements. The RT model uses the floor plan we defined earlier. Each mobility scenario considers that all emergency responders are initially located outside of the incident area and that the ICC is statically located outside of the incident area. Emergency responders enter the incident area from its designated entry/exit points. They can then navigate the rooms within each floor. For each mobility scenario, the selection of the next room (i.e., domain) to move to given the current room is defined probabilistically. The probability of moving from any room to another is defined in a separate file. This is also used to define mission-oriented mobility. For example, a mission can be defined where emergency responders are searching for victims within the incident area and are navigating every room in a floor. In this mission, the probability of moving from one room to the one next to it (e.g., based on the room numbers shown in Figure 1) is 1. The probability of moving to any other room is 0. This can also be used to define group mobility. Emergency responders can utilize the same probabilities when transitioning from a room to another.

C. Breadcrumb System Functionalities

We modeled the functionalities of the 2.4 GHz prototype breadcrumb system in our simulator. The transmission power, receive threshold, carrier sense threshold, data rate, and basic rate parameters in our simulations are chosen to reflect the 2.4 GHz system. All breadcrumbs are configured to operate on channel 11. The breadcrumbs deployment threshold, the default RSS value, and the probe frequency are selected to ensure timely deployment of breadcrumbs so that an emergency responder is not disconnected from the ICC. Table I summarizes the values used for the system parameters.

IV. IMPACT OF INTERFERENCE

A. Simulation Setup

In this section, we use the ns-2 simulator to evaluate the impact of interference on the performance of the breadcrumb system. We consider an emergency scenario to occur in an office building with a floor plan similar to the one shown in Figure 1. We illustrate the impact of unintentional interference (from co-existing networks) as well as that of intentional interference (from jamming attacks). In the case of unintentional interference, we consider the incident area to have a WLAN (Wireless Local Area Network) that consists of six 802.11b access points, three in corridor A and three in corridor B. We model different levels of interference by increasing the number of WLAN clients. When the WLAN has no clients, interference to the breadcrumb system is limited to the WLAN management frames. Increasing the number of clients will increase the WLAN traffic causing more interference to the breadcrumb system. Communication between a WLAN client and its corresponding access point is based on sessions that we generate according to a Poisson distribution with average session arrival rate $\lambda = 0.1\,\mathrm{s}^{-1}$. During each session, a client receives a number of data packets (uniformly distributed on the interval [0, 200] with mean 100 packets) from its access point. For the case of intentional interference, we consider a jamming source that attempts to reduce network performance by increasing noise within the incident area (to decrease signal to noise ratio). The jamming source is positioned randomly within the incident area and transmits at double the transmission power of a breadcrumb. We consider the case when there is no interference (WLAN is off and no jammers) versus when there is interference (WLAN is on or an active jamming attack).

TABLE II. SUMMARY OF SIMULATION PARAMETERS

Num. of emergency responders	1
Num. of breadcrumbs per emergency responder	30
Simulation duration	1200 s
Traffic generator	Constant bit rate (16, 32, 64 kbs^{-1}) 40 bytes packet size
Transport protocol	UDP
Path loss exponents ($\beta_1, \beta_2, \beta_3$)	1.76, 2.05, 4.21 (based on experimental results in [9])
Num. of WLAN clients	0, 6, 12

In our simulations, we consider one emergency responder that is equipped with 30 breadcrumbs. The emergency responder randomly navigates the rooms within the floor for 1200 s at a speed ranging between 1 and 5 meters per second and pause time that ranges between 1 and 5 seconds. Traffic from the emergency responder to the ICC is generated at three different CBR data rates 16 kbs^{-1}, 32 kbs^{-1}, and 64 kbs^{-1}. These data rates reflect a range of voice and data applications that may run independently or concurrently. We assume the UDP (Universal Datagram Protocol) transport layer protocol is employed. Table II shows all the simulation parameters.

We use three performance metrics in our evaluation: packet loss, number of breadcrumbs deployed, and end-to-end delay. Ideally, packet loss and end-to-end delay should be low. The number of breadcrumbs deployed should be enough for the emergency responder to maintain reliable connection to the ICC. Deploying too many breadcrumbs may lead to high contention in the network which increases end-to-end delay and packet loss. Deploying too few breadcrumbs may disconnect the emergency responder's connection to the ICC in the worst case or may result in poor quality links which may also increase packet loss. All results are averaged over 50 simulation scenarios. Each scenario considers a different randomly generated emergency responder mobility and either different WLAN clients' traffic or jammer's location.

B. Simulation Results

Our simulation results indicate that interference impacts the performance of the breadcrumbs system. The severity of the impact is a function of the emergency responder application data rate as well as the interference level as shown in Figures 4-

6. The presence of the WLAN means that nodes in the WLAN and the breadcrumbs have to contend for access to the medium, which results in packet loss. Intentional interference has a greater impact on the network compared to unintentional interference. The jamming attack causes average packet loss to reach 34%, 47%, and 65% in the case of 16, 32, and 64 kbps data rates, respectively. This much higher than the packet loss requirements for speech communications for example, which is expected to range between 5% to 10% according to [12].

Figure 5 shows that the number of breadcrumbs deployed follows a similar trend as packet loss. As interference increases, some of the probe ACKs used to assess link quality are lost. Based on [1], a default RSS value is used whenever a probe ACK is not received by the emergency responder from a given link. This decreases the accuracy of link-quality assessment, which may lead to some links being inaccurately perceived as low quality links resulting in unnecessary breadcrumb deployments. The emergency responder may eventually run out of breadcrumbs and may lose connectivity to the ICC, which contributes to the increase in packet loss shown in Figure 4. Note that the advantage of using a default RSS value is to account for cases where the link between the emergency responder and the next hop breadcrumb towards the ICC suffers from a deep fade resulting in loss of probes and probe ACKs. Using the default RSS value guarantees that the running average of the last N RSS values recorded for the link will go below S_{th}, which triggers breadcrumb deployment.

A similar observation is made in Figure 6 which shows that end-to-end delay increases as the interference level and/or the emergency responder application data rate increases. When interference increases, contention for the medium also increases. This increases queuing delay, which inevitably increases end-to-end delay. Additionally, end-to-end delay increases as the number of breadcrumbs deployed increases. According to [2], the maximum acceptable end-to-end delay for voice applications in public safety communication systems is 200ms. This was further refined for speech communication in mission-critical networks in [12] showing that no negative effects for mouth-to-ear delay as long as end-to-end delay is bounded by 150ms. Figure 6 shows that end-to-end delay may reach 400ms due to interference from the WLAN and approaches 1sec when the breadcrumb channel is under a jamming attack.

V. UTILIZING THE COGNITIVE RADIO TECHNOLOGY

A cognitive radio is aware of its RF environment, can adapt its own PHY and MAC layer parameters to optimize its performance, and can learn from the outcome of its prior actions. The cognitive radio technology has the potential of alleviating some of the problems hindering public safety communication such as spectrum scarcity, lack of capabilities, lack of interoperability between different public safety agencies, as well as interference detection and resolution. We are considering the cognitive radio technology for the next generation breadcrumb system for all the above reasons. For example, the cognitive radio equipped breadcrumbs can act as a gateway between emergency responders that belong to different agencies or jurisdictions (i.e., operate on different communication channels) within an incident area. However, we focus in this section on the interference detection and resolution potential of the cognitive radio technology.

We have developed cognitive radio functionalities in ns-2 to allow breadcrumbs to perform spectrum sensing, spectrum analysis, and spectrum decision operations [13]. The cognitive radio model assumes that all nodes are aware of the set of utilizable channels $B = \{b_1, ..., b_m\}$. Also, a common broadcast channel is available that breadcrumbs use for broadcast and control messages. We assume that all nodes are synchronized. This is necessary in cognitive radio networks to avoid confusion between primary user (i.e., interference sources) and secondary users transmissions [14].

Initially, each breadcrumb senses energy activity on its current channel only for 5ms every 1sec. A breadcrumb remains tuned to its current channel if no activity was sensed on it. Otherwise, full spectrum sensing is triggered where each node tunes and senses activity on each channel $b_i \in B$ for 5ms (for a total sensing time of $5 \times m$ ms). At the end of full spectrum sensing, each breadcrumb generates $S = \{s_1, ..., s_m\}$, a map of the spectrum occupancy within its locality, where $s_i = \begin{cases} 1, \text{if activity was sensed on channel } b_i \\ 0, \text{if no activity was sensed on channel } b_i \end{cases}$. Control then shifts to the cognitive radio spectrum analysis and decision functionality, which randomly selects a new channel amongst the available ones. The breadcrumb then informs its neighbors of its new channel. This information is utilized when two breadcrumbs want to communicate but operate on two different channels. In such cases, we always consider the transmitter to tune to the channel used by the receiver. The cognitive radio spectrum sensing operation is shown in Figure 10.

We re-evaluate the performance of the cognitive radio equipped breadcrumb system in the presence of interference using the same simulation scenarios discussed in Section 4. We consider $|B| = 10$ (i.e., ten utilizable channels). Our results (shown in Figures 7, 8, and 9) show performance enhancements with respect to throughput, number of breadcrumbs deployed, and end-to-end delay when cognitive radios are deployed. The cognitive radio at each breadcrumb autonomously detects interference from the WLAN and migrates to a different interference free channel (or one with least interference). This reduces the impact of interference on the system. Note that under favorable conditions (i.e., no interference) the hardware radio breadcrumb system has slightly lower packet loss and lower end-to-end delay than the cognitive radio system. The impact is particularly apparent in end-to-end delay. The cognitive radio channel switching and channel sensing operations result in some increase in packet loss and delay. A breadcrumb is not tuned to its data channel when it is transmitting to a receiver that is on a different channel and when it is sensing the spectrum. All packets in the breadcrumb's queue will have to wait until the breadcrumb switches back to its data channel, which increase queuing delay. Also, all attempts to reach the breadcrumb (to relay traffic) will fail, which also increases delay and leads to packet loss. However, this overhead of the cognitive radio operations is independent of interference, which makes the system more reliable. Cross-layer optimization and collaborative techniques can be utilized to inform upper layer protocols as well as neighbors of a breadcrumb of its channel switching and sensing operations so as to reduce their impact on the system performance.

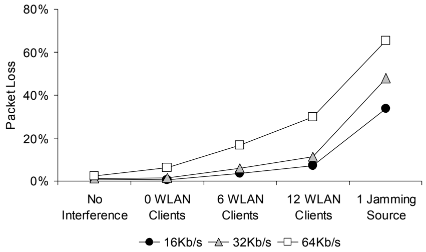

Figure 4. Impact of interference on packet loss

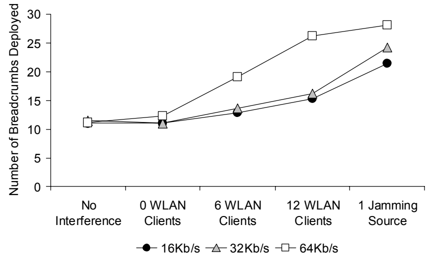

Figure 5. Impact of interference on breadcrumb deployment

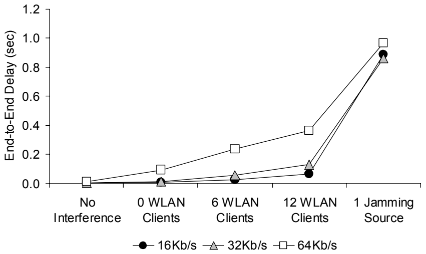

Figure 6. Impact of interference on end-to-end delay

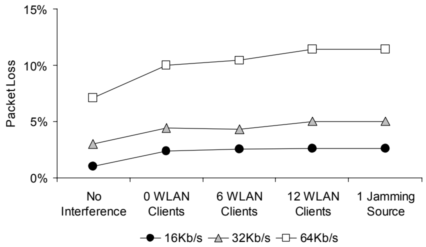

Figure 7. Impact of interference on packet loss (using the cognitive radio technology)

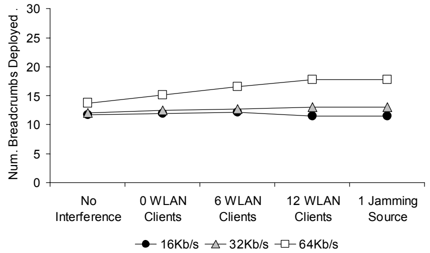

Figure 8. Impact of interference on breadcrumb deployment (using the cognitive radio technology)

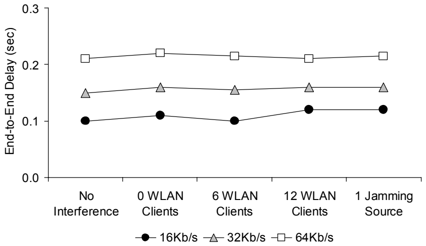

Figure 9. Impact of interference on end-to-end delay (using the cognitive radio technology)

VI. CONCLUSIONS AND FUTURE WORK

Multi-hop relays such as the breadcrumb system can be utilized to extend the communication range of public safety communication systems in indoor environments. However, the lack of *a priori* knowledge of the communication environment within an incident area may result in poor network performance. Communication in some environments may be impeded by harsh radio propagation conditions or the presence of RF interference sources.

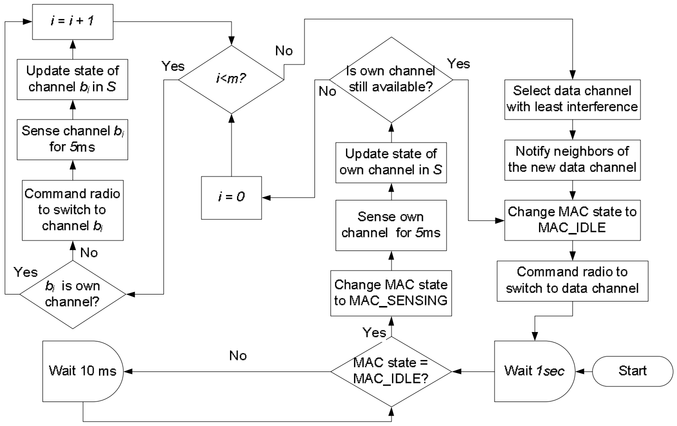

Figure 10. Cognitive radio spectrum sensing operation

In this paper, we have developed a simulation model for the breadcrumb system and used it to show that interference can deteriorate the performance of the breadcrumb system. The presence of interference sources increases packet loss, end-to-end delay, and results in unnecessary deployments of breadcrumbs. We have illustrated how the cognitive radio technology can be utilized to alleviate the impact of interference on the system. Cognitive radios can detect the presence of interference sources and select better channels to tune to. Our current work focuses on analyzing the impact of cognitive radio functionalities (spectrum sensing and spectrum mobility [13]) on the performance of upper layer protocols and applications in public safety communication systems. We are devising cross-layer mechanisms to bring awareness of the cognitive radio operations to higher layer protocol stacks (application, routing, and transport layers).

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