CORPS: Event-Driven Incident Mobility Model For First Responders

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***Abstract*—Mobility patterns of first responders (FRs) in incident scene have distinct properties from patterns of other human groups, such as drivers on road and college students on campus. FRs are mission-oriented. They are organized, cooperative and responsive to emergency situations. Although emergency responding is one of the major applications of mobile ad hoc networks, it is regrettable to note that most of existing mobility models fail to capture these unique properties of first responders. Therefore, protocols, evaluated under unrealistic mobility patterns in simulation, present incorrect estimated performance in real deployed networks. In this paper, we propose a novel mobility model, CORPS, which captures both environmental and operational determinants for FRs' movement. CORPS is an event-driven mobility model with event-oriented characterization. Experiments show that CORPS reflects mission-oriented operational logistics of FRs and yields distinct topology characteristics and application performance.**

***Index Terms*—Mobility Model, Event, Performance Measurement**

I. Introduction

Public safety incidents occur in diverse environments with little predictability. To ensure survivability of first responders (FRs) and maximize their execution effectiveness, they are equipped with sensors and mobile communication devices. Sensors monitor the operating environment and personnel status. Wireless devices support both real-time voice communication and information exchange, such as location, health and environment monitoring data, and alert [1]. Due to the large area of incident scene and radio degradation from interference and obstacles, wireless devices often form multi-hop networks under resource constraints to enable both group communication and personnel-to-command-center communication. The quality of communication and resource allocation highly depend on network topology, which is in turn determined by movements of on-scene FRs. Bai et. in [2] show that different routing protocols present unique properties under different mobility models, such as throughput and control overhead. There is emerging consensus that protocol design and distributed systems should be studied under realistic and scenario-specific mobility models, considering temporary dependency [3], spatial dependency [4], geographic constraints [5] and empirical measurement of social effects [6]. This means that in simulation-based evaluation of routing and application protocols for incident scene ad hoc wireless networks, it is crucial to use authentic mobility models for first responders.

In order to obtain a realistic mobility model, we made several efforts to understand movement properties of FRs. First, we had intensive discussions with researchers and firefighters. Professor Scott Poole, whose research covers group communication among firefighters, helped us execute a survey of movement patterns among firefighters. We interviewed Dr. Gavin Horn, a training instructor from the Illinois Fire Service Institute (IFSI), about operation logistics of rescue missions in years 2007 and 2008. Second, we studied training materials and requirement statement from the Department of Homeland Security [1]. Finally, we visited the training facility of IFSI, located in Champaign IL, to inspect the physical training environment of rescue operations, such as 2-story commercial burning building and 6-story burn tower. The primary findings were that first responders are mission-oriented and their movement must reflect the fact that they are organized, cooperative and responsive to emergency and mission-critical situations. First, FRs are *organized*. They are from various organizations and agencies with different missions. FRs with the same mission form a group. Different groups have diverse execution goals, targets and task sequences. They react to distributed incidents and emergency situations differently. For example, a bomb expert and an EMS (Emergency Medical Service) staff may have different coverage regions. The former is interested in bombs while the latter provides first aid to victims and patients. Second, FRs are *cooperative*. There exists tight cooperation inside groups. Group members shield one another from dangers and coordinate in emergency situations. For instance, two-in-two-out policy mandates that firefighters never go into a dangerous situation in a fire or rescue incident alone. This coordination relationship might be dynamic, depending on the emergency situation and their mission. Third, FRs are responding and interacting with dynamic environments. For example, lethal explosion could totally prevent FRs from entering except if they are fully protected. For those individuals authorized to enter, they may move slowly with caution due to potential danger and low visibility. Furthermore, the incident scene environment is changing unpredictably because of random events, such as abrupt fires and explosions. First responders are driven by emergency situations and incidents upon approach or encounter, which leads to unpredictable mobility patterns. To summarize, movement patterns of FRs should mirror the features such as their Cooperation, Organization, and Responsiveness for Public Safety (CORPS property for short).

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There are two ways to build mobility models, trace collection and synthetic models. Collected over a long period of time [6][7], traces are either used directly in simulation or used to train synthetic models [8]. Despite trace's authenticity, empirical mobility models from traces are not applicable to FRs. First, mobility traces for FRs are often unavailable from public access, due to concern about security, victims' privacy and misuse by terrorists. Second, substantive traces, if any, with statistical significance for FRs are hard to collect due to rareness of large-scale incidents and their relative short duration. Third, traces highly depend on incident environments and dispatch decision, hard to generalize. Finally, traces can be replayed only during the simulation, and cases, such as human movement altered by message exchange, cannot be modeled. Synthetic models, on the other hand, are easy to obtain with manipulable parameters and can be easily integrated with network simulator. Examples are random waypoint [9], random walk [10], and smooth mobility models [3]. Other models for concrete scenarios are Pathway [11] and obstacles [5] models for campus WLAN, STRAW model [12] for vehicular networks and reference point group mobility model [4][13] for group operation. However, existing synthetic models are inadequate to capture unique properties of FR movement patterns, which are mostly determined by dynamic environment and operational logistics (organization, cooperation and responsiveness) [14].

Due to the disadvantages of trace collection, we adopt the method of synthetic model for FR mobility pattern. The synthetic model is enriched with operational logistic and environment determinants; yet it is constructed concisely so that users, with a little configuration overhead, can capture the incident scene and first responders' operation and mobility comprehensively. The synthetic mobility model is called "CORPS", which reflects the CORPS property. The core of CORPS is a sequence of physical events that drives FRs' movement, such as trapped victim and explosion. Events define both mission and mutative environment, which then define FRs' mobility patterns. CORPS property is enforced by the interaction between FRs and events in physical environments. In CORPS we propose (i) a new destination selection process to reflect cooperation, organization and responsiveness; (ii) a new path calculation process to reflect how FRs react to obstacles and dangerous areas; and (iii) movement of microgroup to model two-in-two-out policy.

The rest of the paper is organized as follows. Section II describes three components of the CORPS mobility model. In Section III, we present how to decide the movement trajectory for an FR. In Section IV, we evaluate the realism of our model and reveal the difference of routing and application protocol performances for CORPS and modified random waypoint mobility model. Section V presents related work and concluding remarks are given in Section VI.

II. CORPS Mobility Model

CORPS mobility model is composed of three components: first responder model, event model, and environment model. FR model captures user-specific parameters that are known prior to the deployment at an incident scene. Event model captures physical events happening in time and space, e.g. a building burning at 3pm, located in John Street. Events are connected to either missions and tasks (attention events) or situations in mutative dangerous areas (caution events). Environment model is a personalized zone view, composed of all events and untraversable obstacles, which affect FRs' mobility patterns.

Given a list of first responders and a list of events with populated attributes, environment model is created per first responder. Based on this personalized zone view, we use movement calculation process, discussed in Section III, to derive mobility trajectory for each FR. The output of the movement calculation is a sequence of time-position tuples.

A. First Responder User Model

First responders are users with missions, who search for target incidents and solve them, within their coverage area in the incident scene. First responders from the same organization form a natural group. But they may bear different missions. We use role to indicate mission-level macrogroups. For example, firefighters of role 1 search for survivors, while firefighters of role 2 extinguish fire. Each person is labeled with a role. People of the same role compose a macrogroup. Macrogroup members have similar attributes and cooperate on events; however, they move independently from each other, except when solving incidents. Two FRs may be organized in a so-called buddy-buddy system, as in two-in-two-out policy. We call this grouping of two spatial-dependent FRs a microgroup. Two FRs from a microgroup always move in close proximity, work in the same mode and assist the same mission. A microgroup consists of a leader and a follower. Followers follow leaders' movement passively. In Figure 1(b), Node 1 and 2 form a microgroup. Node 1 moves from the current position to the destination in dotted line. The follower Node 2 follows Node 1's trajectory with a small degree of variation.

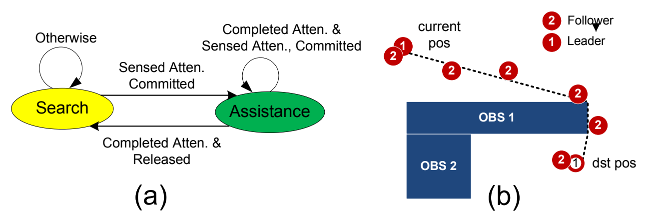


Fig. 1. Working Mode, Movement

FRs work alternatively in two modes, search mode and assistance mode. In *search mode*, an FR looks for attention events by randomly moving inside his coverage region. Upon detecting an attention event which needs additional assistance from FRs, he commits himself to this mission (event) and transfers to *assistance mode*. While working on this mission, he moves randomly in a confined area around this event. Upon mission completion, he is released and enters search mode again. Transition between two modes is shown in Figure 1(a).

Multiple FRs can commit to an attention event at the same time. Anytime, an FR commits to at most one event. It is possible that several FRs compete for commitment to the same attention event if they detect it at the same time. How to arrange commitment assignment can be formalized as a set of policies involving event criticality, FRs' distance from the events, and resource availability. In this paper, we let the FR with the lowest ID commit.

When a first responder moves in the incident scene, he usually has a destination in mind. (In search mode, the destination is a random location inside his coverage region.) An FR always moves towards the destination in shortest-safe path, which is a shortest-distance path, avoiding all the static obstacles and dangerous areas as shown in Figure 1(b). Node 1 avoids two rectangular obstacles.

We use the following parameters to characterize an FR at an incident scene. These attributes capture coarse-level dispatch and typical mobility features known before FRs' deployment.

1) Role: a numerical value specifies the FR's role during the incident and implicitly defines the types of events and incidents which an FR pays attention and responds to.

2) Working Hour Information: includes arrival time when an FR begins his shift (enters the scene), departure time when an FR wraps up the current task/mission and finishes his shift (leaves the scene).

3) Coverage Region: is an area, in which an FR moves, while in search mode. It also specifies an entry point and a set of exit points. At the beginning (end) of the shift, an FR moves from (to) the entry point (a nearest exit point) to (from) his coverage region.

4) Speed Range: specifies a viable range of FRs' moving speed. It depends on transportation means. An FR's speed at any time is a random value generated from this range.

5) Displace Radius and Gap Range: quantize how much movement diversity exists in the microgroup. Displace Radius is the maximal distance between two FRs from a microgroup. Details are explained in Section III.

Fig. 2. First Responder Attributes

Figure 2 illustrates the above attributes in a tunnel rescue mission. Two agencies (police and EMS) are assigned three roles (two police groups and an EMS group). Policemen are deployed in Phase 1 and EMS is deployed in Phase 2. FRs of three roles have different coverage regions. EMS and Police Group 2 are around cordon areas at two ends of the tunnel. Police Group 1 is working in the tunnel. The set of entry and exit points are shown as "EXIT".

B. Event Model

An event is something that happens at some place and time. Here we only care about those events which impact the mobility patterns of FRs. Events are classified into two types, namely attention and caution events, which attract and repel FRs from their areas. *Attention* events are connected to missions and tasks, which need timely assistance from FRs, such as a trapped victim or a patient needing first aid. They attract FRs to work inside the defined attending zones. An attention event diminishes as being *completed* when enough FRs have attended to it for the required duration before its lifetime. Otherwise, it is considered as being *failed*. *Caution* events are situations connected to dangerous areas (also called forbidden zones), such as chemical spill and explosion. FRs generally do not step into the associated forbidden zones for safety reason. For simplicity, we assume that attention and caution events are static with respect to geographic locations and dynamic with respect to their lifetime. Attracting and repelling relationships are defined per role, such as event A attracts (warns) role i. An event could be an attention and caution event simultaneously but to different FR roles. We use the following attributes to model an event:

1) Central Location with sensing range: is used to model the scope of events' visibility. An event can be detected by all first responders who are situated within the sensing range around the central location.

2) Attending Role List with attending weight: enumerates the roles of FRs who can commit to this attention event. Attending weight defines the maximal number of FRs who can commit to it at any time. An attention event requiring a higher degree of coordination has a higher attending weight.

3) Forbidden Role List: enumerates the roles of FRs forbidden to enter the forbidden zone of a caution event.

4) Attending Zone: outlines a rectangular area around the central location, wherein FRs committed to this event move inside.

5) Forbidden Zone: outlines a rectangular area around the central location, wherein FRs on forbidden role list must bypass.

6) Event time: is a time point when an event starts.

7) Lifetime: is the duration over which an event expires if it is not attended by an FR after its lifetime.

8) Resolution Effort: is the amount of effort, in unit of time, required to resolve an attention event (mission). If n FRs are committed to this event, the absolute resolution time is shortened n times.

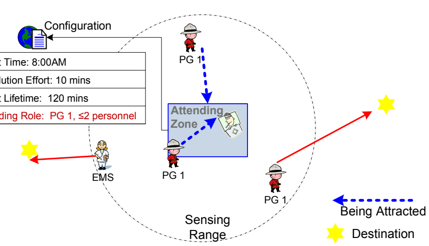


Fig. 3. Attention Event

Considering the tunnel rescue example in Figure 2, we show an attention event of a victim trapped in a crashed car, which is interesting to Police Group 1 (PG 1) in Figure 3. This event starts at 8:00AM and has a lifetime of 2 hours. Its resolution effort is 10 minutes. It attracts 2 police officers towards its attending zone. The absolute resolution time is reduced to 10/2 = 5 minutes after 2 police officers arrive inside the attending zone. The third policeman is unaffected since this event has already attracted the maximal number of policemen from Group 1.

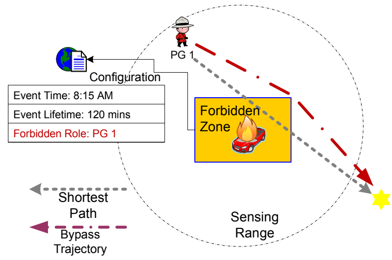


Fig. 4. Caution Event

An example of a caution event is shown in Figure 4. This caution event corresponds to an unexpected car explosion, which happens at 8:15AM during rescue effort. The area around the car explosion becomes forbidden zone, hence dangerous for FRs from PG 1. This means that each policeman from PG 1 will detour the forbidden zone via a longer but safe route.

C. Environment Model

Each FR views an incident scene as a spatial area overlaid with attending/forbidden zones, and obstacles, updated continuously. We call this overlaid information a *personal zone view* as shown in Figure 5. This zone view largely controls an FRs working mode, how an FR chooses his next destination and the resulting moving trajectory. A personal zone view has the following properties:

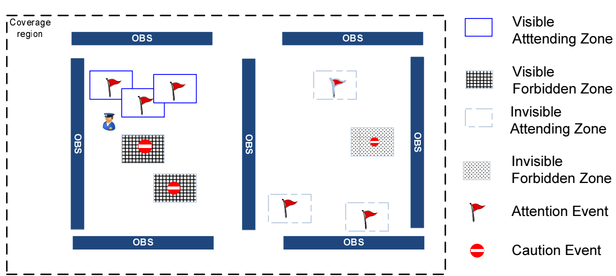


Fig. 5. Personal Zone View

1) Personal zone view is individual-specific. FRs of different roles have diversified perception of attention and caution events.
2) Personal zone view varies with time. Zones appear to FRs upon approaching and dissolve when their associated event is completed or fails.

In the environment model, obstacles define the feasible movement trajectories for FRs, such as walls, obstructions and buildings. First responders cannot traverse through obstacles for any reason. Our event characterization can be flexibly used to model obstacles, even though there are no physical incidents. We define obstacles as caution events with event time 0 and a lifetime spanning the whole incident scene lifetime. They have empty attending role list and repel all roles. Despite the rectangular shape of forbidden zones, we are able to model complex outdoor and indoor environments as shown in Figure 6. A room with a door can be modeled with four rectangular obstacles.

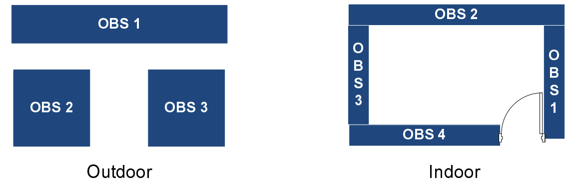


Fig. 6. Physical Environment

As we can see, our event-oriented characterization is very general and flexible to model many facts of an incident scene, from physical environment to incidents. It is worthwhile to mention some salient features of CORPS. Coverage region with entry/exit points provides us with a realistic initial node distribution. Working hour information models phased deployment, where multiple batches of first responders dynamically enter and leave the network. Attention events can be extended to model commands, which are central dispatch directives from command centers. They are associated with missions and movement. Examples of commands are “Three FRs of role 1 examine the kitchen of apartment 21B in building X” and “FR 1 and FR 2 rescue victims in classroom A”. We use attention events with unlimited sensing range to model those central dispatch command. Event time is set to the issuing time of the command. The attending role list can be supplemented by attending ID list to specify the set of FRs affected by this command, like “FR 1 and FR 2” in the above example.

III. Movement Calculation

Movement is the result of interaction among first responders and events in the personal zone view. A first responder moves around within his coverage region, searches for attention events and transfers between search and assistance modes, avoiding all sensed forbidden zones. Many mobility models are built on a repeated process of (a) selecting a destination, (b) moving towards destination and (c) staying at destination for random duration. CORPS is built on this simple process as well. However, we have refined the following components to capture CORPS features, i.e. destination selection, movement behavior at destination, and physical path calculation. This movement calculation is mainly for group leaders in microgroups. Since followers passively follow the moving decision of leaders, their movement calculation is presented separately.

A. CORPS Movement for Group Leaders

1) Destination Selection: Because first responders are task-oriented, destination is chosen based on their assigned tasks, thus their working mode. In search mode, destination is selected to be a location inside his coverage region. In assistance mode, destination is a location inside the attending zone of the committed event.

Despite the simplicity of this destination selection process, we can model progressive destination selection by extending the concept of attending zone (AZ) and sensing range to a hierarchy of overlapping AZs and sensing ranges. As users move closer to the physical incidents, they have more refined moving area. An example is shown in Figure 7. Attention event E is associate with three-level attending zones of A, B and C.

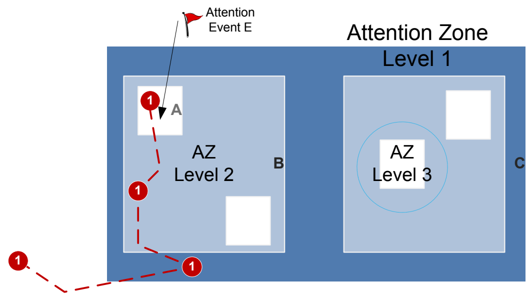


Fig. 7. Hierarchical Attending Zones

C has larger sensing range (not shown in the picture) than B, and B has larger range than A. Additionally, C has larger AZ than B, and B has larger AZ than A, which is the smallest unit of AZ. Node 1 progressively senses level-1, level-2 and level-3 AZs for E and moves until the attention zone A, and then works on E in assistance mode.

2) Movement behavior at Destination: Due to emergency, FRs continuously move in the network without pause.

3) Shortest-Safe Path Calculation: Incident scene spans impenetrable dangerous areas and obstacles. Forbidden zones and caution events are used to model those dangerous areas and obstacles, which prevent FRs from moving towards destination in a straight line. A shortest-safe path is a path to the destination of the shortest distance, among all the paths which do not crossover any forbidden zones. Here we propose a novel shortest-safe path calculation algorithm. The output is a list of turning positions. An FR moves from one turn to another in a straight line at a constant speed within speed range. Path is recalculated whenever a new destination is selected or a new/expired caution event is detected.

We use Dijkstra's algorithm to calculate the shortest path from current location S to destination location D, avoiding a set of m forbidden zones $FZs = \{FZ_i, 1 \leq i \leq m\}$. We assume that all the forbidden zones $FZ_i, (1 \leq i \leq m)$ are rectangular. The vertex set of those zones is $V(FZs) = \{v | \forall FZ_i, FZ_i \in FZs, v \text{ is a corner vertex of } FZ_i\}$. If the straight line from S to D is NOT blocked by any forbidden zone, the shortest-safe path is this direct path. The rest of discussion assumes that the straight line is blocked by some caution events.

Assumption of rectangular shape for forbidden zones renders the following property: The shortest path always turns at corners (turning positions) of forbidden zones. As shown in Figure 8(a), the optimal path is the dashed line and two alternative non-shortest but safe paths are solid bold lines. With the above property, we can solve this shortest-safe path problem using Dijkstra's algorithm instead of exhaustive enumeration on the 2-dimensional plane. The input of the Dijkstra's algorithm is a weighted undirected graph G. The set of vertices consists of S, D and all the vertices of forbidden zones $V(G) = \{S, D, V(FZs)\}$. The set of edges $E(G)$ is composed of all the pairs of vertices (u, v) whose straight line is neither intersected by nor inside any forbidden zone . The weight of edge (u, v) is the Euclidean distance between u and v. Figure 8(b) shows the generated graph G of Figure 8(a), which has 14 labeled vertices.

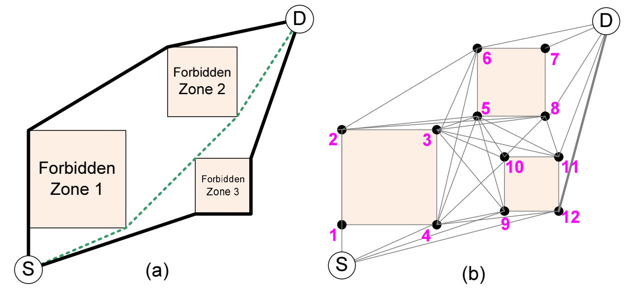


Fig. 8. Shortest & Safe Trajectory

Dijkstra's algorithm will output the shortest path from S to D with turns at various corner vertices of forbidden zones. In this example, the output is the ordered list of turning coordinates corresponding to vertex 4, 10 and 8.

B. CORPS Movement for Followers

In search mode, a leader scans the network area for potential attention events. A follower adjusts his trajectory from time to time to approximate his leader's trajectory/movement[1]. We use *displace region* and *displace gap* to parameterize movement diversity of followers. The trajectory approximation algorithm of the follower is as follows.

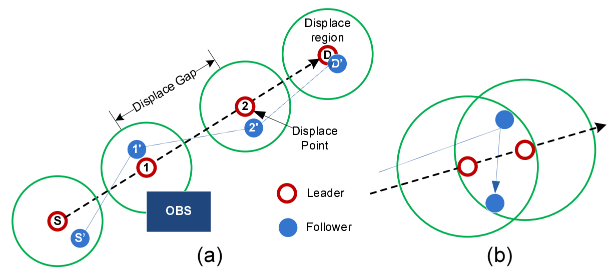


Fig. 9. Spatial Dependency between buddies

Let us assume that the follower is at the location S' and the leader plans to move from location S to location D in a straight line, passing a list of intermediate displace locations from 1 to k. We append D to this list as $(k+1)_{th}$ location. The follower will pass another list of intermediate locations from 1' to $(k+1)'$, such that (a) location i' is a random location within the displace region around location i; and (b) when leader arrives at location i, follower arrives at location i'. $(k+1)'_{th}$ location is the destination location D' for follower. An example is shown in Figure 9(a). Size of the displace region is specified via displace radius and the distance between two adjacent displace locations must be within the displace gap range. The larger the displace radius is or the smaller the gap is, the more movement diversity the follower has. Considering overlapping possibility of displace region and forbidden zones, the area of forbidden zones should not be selected as the intermediate locations, as shown in Displace Region around location 1 of Figure 9(a). If we desire to eliminate the pathological cases when followers move backward, the minimal displace gap should be at least twice the region radius, as shown in in Figure 9(b).

[1]In assistance mode, a follower does not approximate his/her leader's trajectory, considering the relative small area of attending zone.

TABLE I
EVENT CONFIGURATION

	Class 1	Class 2	Class 3
No. Prior Events	[1, 2]	-	-
Inter-arrival Time	6 min	-	-
Resolution Effort	[10, 20] $lbr \cdot min$	-	-
Lifetime	30 min	-	-
Sensing Range	[100, 150] m	-	-
Attending Zone	W[20,30]m; L[20,30]m	-	-
Attending Role	1	2	3
Attending weight	[3, 5]	-	-
Forbidden Roles	{2, 3}	{1, 3}	{1, 2}

[min, max]: uniform distribution in range from min to max;
-: the same configuration as Class 1; W: Width; L: Length
Prior Events: Event with Event Time 0;
Inter-arrival Time: Time interval between two adjacent events;

TABLE II
FIRST RESPONDER CONFIGURATION & OTHER

Shift Period	30 min
Phase Interval	30 min
Speed	[3, 6]m/s
No. Phases	2
Roles	{1, 2, 3}
Coverage Region	Network Area
Phase Composition	12 from each role w. microgroup
Network Area	1000m * 1000m
Entry/Exit point	Coordinate (1000, 5000)

IV. EXPERIMENT

In this section, we study the fidelity of CORPS to model first responder mobility patterns, necessity of microgroup, network topological characteristics and performance of gossip-based broadcast when first responders move according to CORPS. As a comparison to CORPS, we propose modified random waypoint mobility model (mRWP), which removes various unrealistic assumptions of random waypoint mobility model (RWP), such as as (1) random initial distribution of users when network starts, and (2) traversal through forbidden zones. In mRWP, users move in almost the same way as CORPS, except that they are *not mission-oriented*. They have no concept of attending zones or attention events. They are always in search mode and avoid forbidden zones. They understand the concept of coverage region, entry and exit locations and working hour information. We can view mRWP as a sub-model of CORPS, since mRWP establishes mobility patterns without organization, collaboration and responsiveness to attention events. All the simulations are performed in our own simulator implemented in MATLAB.

The simulated scenarios contain 3 FR roles and 3 classes of events. Events of the same class have almost identical attributes. The configuration of FRs and events are summarized in Table I and Table II. All attention events have one level of sensing range and AZ. Events of class i attract FRs of role i and warn the other two roles, $i = \{1, 2, 3\}$. Forbidden zone is configured as the same area as the attending zone. Twelve first responders of each role are dispatched into 1000m*1000m network in each of the two phases. There is an entry and exit location at coordinate location (1000, 500). Six obstacles of size 150m*150m are regularly placed in network and known to all FRs, as shown in Figure 11. Coverage region is the whole network area.

A. Fidelity of CORPS

In this experiment, we evaluate FRs' effectiveness in terms of number of completed attention events. Since FRs are mission-oriented, this metrics shows how CORPS captures the operational logistics of FRs authentically. An attention event is completed if all the FRs, who have committed to this event, have stayed in its attending zone for resolution effort worth amount of time. Because nodes in mRWP do not understand attention events or mission, we measure the total time duration all the FRs staying in this event's attending zone, whose role matches its attending role list. If this time duration is greater than resolution effort, we assume this event is completed.

TABLE III
NO. OF COMPLETED EVENTS

	Scen. 1 (26)	Scen. 2 (36)	Scen. 3 (36)
CORPS	24	25.2	28.8
mRWP	0	0	0

An incident scene scenario (configuration) is uniquely defined by a list of first responders and a list of events with populated attributes. We have plotted the results for 3 scenarios with different event configurations separately, because the physical layout of attention events determines how effectively FRs are able to locate them. In a scenario with events closely distributed, FRs can easily find out all the attention events; while in a scenario with events distributed sparsely along the boundary of FRs' coverage region, FRs have hard time locating them since they rarely hit the boundary of their coverage region. Scenario 1 has 26 attention events; scenario 2 and scenario 3 have 36 attention events. As we can see from Table III, FRs in CORPS solve most the attention events; while in mRPW, FRs solve zero events. This result is reasonable and intuitive, because in mRWP, FRs are not mission oriented and their random movement causes the total time duration they spend in any small region inside the network to be very short, compared to the required resolution effort to solve an attention event.

Another important feature, which makes CORPS an authentic mobility model for FRs, is that FRs avoid all the caution zones and obstacles. Compared with other mobility models without concept of obstacles, such as RWP and Smooth mobility model, CORPS gives more fidelity because we never place FRs inside dangerous areas or obstacles.

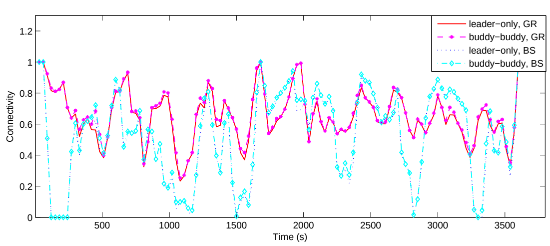
B. Necessity of Microgroup?

In this experiment, we investigate whether we need microgroup concept in CORPS. It is true that microgroup models two-in-two-out policy in buddy-buddy system, which is a common practice or even enforcement for emergency responding situations. Thus a realistic mobility model should include microgroup. But we are uncertain how big difference microgroup really imposes in network connectivity or in the simulated routing and application protocol performance. Since two FRs always move within proximity, we can view them virtually as a single node, expecting that network connectivity does not change too much. If our hypothesis and expectations prove correct, we could halve the simulation overhead in future

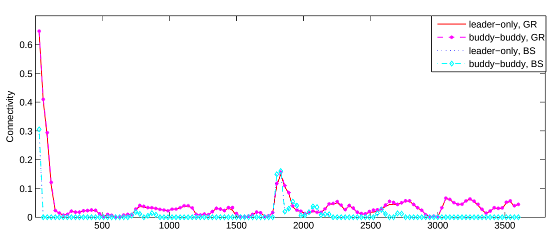
FR mobility model due to working with half of the considered nodes (microgroup merges into a single node.).

Here, we consider two types of connectivity, group connectivity (GR) and first-responder-to-base-station connectivity (BS) over time in Figure 10. A group is composed of FRs of the same role. The base station is placed at the entry point. A connection $c(i, j)$ between node i and j exists at time t if there is a communication path between i and j at t, either direct or multi-hop through other nodes. GR connectivity measures how well FRs of the same role are connected. GR connectivity for group g at time t is defined as $\frac{|\{(i,j)|i\in g, j\in g, c(i,j) \text{ exists at } t, i\neq j\}|}{|g|(|g|-1)}$, where $||$ denotes the size of the set. Because two FRs inside a microgroup are always connected, we only consider node i and node j in the above formula if i and j are group leaders of two distinct microgroups[2]. BS Connectivity measures how well FRs are connected to BS. BS Connectivity of group g at time t is defined as $\frac{|\{i|i\in g, c(i,BS) \text{ exists at } t\}|}{|g|}$. Again, we only consider node i if node i is the leader of some microgroup. We obtain a single connectivity metrics at time t by averaging over all three roles for GR and BS.

In order to evaluate the necessity of microgroup, we measure the network connectivity in two cases: (a) leader only, wherein FRs are composed with group leaders only; (b) buddy-buddy system wherein FRs are composed with group leaders and followers, thus with microgroup. Displace Gap Region is between 20m and 23m and Displace Radius is 10m. The time series of connectivity is a moving average over 60 seconds.



(a) Tx Range = 250m, Displace Radius = 10m



(b) Tx Range = 50m, Displace Radius = 10m

Fig. 10. Connectivity

When the transmission range is 250m (see Figure 10(a)), which is very large compared to Displace Radius 10m, buddy-buddy system definitely improves the network connectivity, but the two curves (leader-only and buddy-buddy) are very close to each other for most of the time for both GR and BS connectivity. When the transmission range is 50m (see Figure 10(b)), which is comparable to Displace Radius, the two curves are close to each other as well. The possible explanation is that the network is almost disconnected with transmission range of 50m; hence even microgroups do not help with connectivity.

[2]A multihop communication path may span both leaders and followers.

The conclusion from this study is that with the similar incident scene configuration as in our experiment, we can merge microgroup into a single node in CORPS to save half of the simulation overhead, but still achieve very accurate protocol performance evaluation. Whether microgroup is necessary or not really depends on the incident scene configuration and needs to be tested case by case. Microgroups should be enabled if intricate protocol behaviors are to be examined and high-confidence performance evaluation in simulation is desired.

Due to the above finding, in the following experiments, we will assume that FRs are composed of leaders only without considering the details of microgroup. Hence, in each phase, 6 FRs from each role are dispatched, instead of 12 FRs.

C. *Topological Characteristics*

1) Accumulated Density Distribution: In this experiment, we compare the accumulated density distribution for both CORPS and mRWP under Scen. 2, as shown in Figure 11. Different styles of small squares represent attending zones for events of different classes. Those events may activate and expire at different time instances, though we show them all together. Obstacles are big solid black squares.

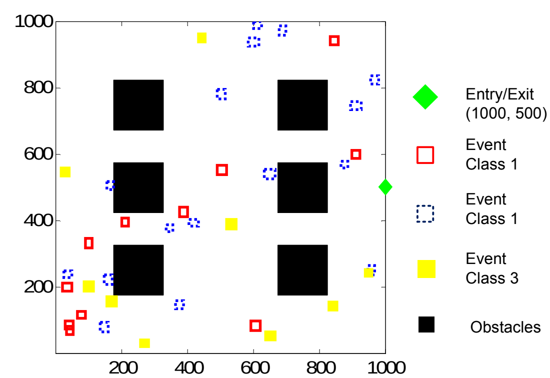
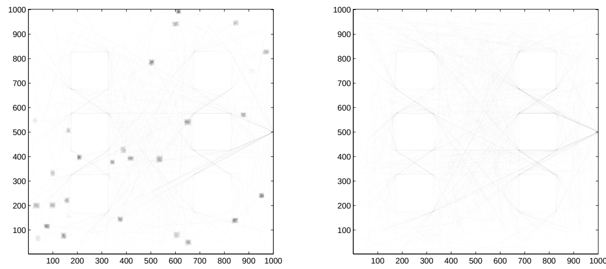


Fig. 11. Event Topology (Scen. 2)

For each $2m * 2m$ location area l within the incident area, we plot the total time duration all FRs reside in l (An FR may stay in l for multiple visits). This time duration at l is directly proportional to the darkness of the point at l. Figure 12(a) shows that the density distribution for CORPS is uneven. FRs stay at locations inside the attending zones of events for longer duration than other locations. On the other hand, the distribution for mRWP in Figure 12(b) is relatively even and less clustered. Several clear grey lines appear in both figures, which are some portion of the shortest paths from a corner of one forbidden zone to a corner of another forbidden zone.

2) Importance of Collaboration: In this experiment, we study the impact of collaboration across different roles on network connectivity for both CORPS and mRWP. Transmission range of devices carried by FRs is set to 250m.



(a) CORPS (b) mRWPS

Fig. 12. Density Distribution

Device compatibility is a big issue because of legacy devices, proliferation of network prototypes and protocols, operating frequencies, and administrative barriers. Devices from two agencies are not able to share resources and exchange information even if they are within the transmission range of each other. Therefore, we study how FRs can benefit from universal device communication and resource sharing (CL), and communication connectivity in particular. We study both group (GR) communication and first-responder-to-base-station (BS) communication as before.

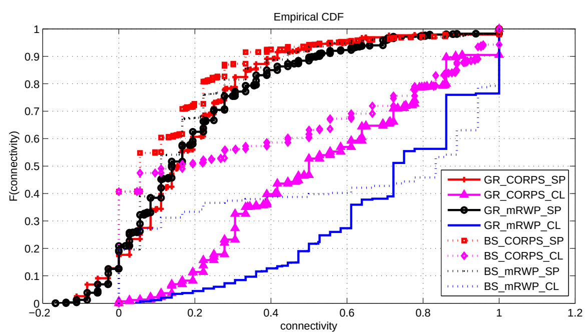


Fig. 13. GR: Group Comm.; BS: Base Station Comm.;
CL: With Collaboration; SP: Without Collaboration (separated)

Figure 13 shows the cumulative distribution function of connectivity. Connectivity for mRWP is generally better than CORPS. The reason is that in mRWP, FRs are distributed more evenly in network and hence FRs have a higher probability to be connected with each other or with base station. For example, connectivity of BS communication with collaboration is higher than 0.4 for 60 percent of time under mRWP and only 40 percent of time under CORPS. Collaboration across groups improves connectivity. For group communication under CORPS, connectivity is higher than 0.4 for about 60% time with collaboration; while it is only for about 10% time without collaboration. Connectivity for BS communication is worse than that for group communication because FRs tend to move far away from the base station during their mission. It stresses the importance of droppable radio bridges to establish persistent communication channel to BS [15]. When FRs do not collaborate, network connectivity is bad, considering 6 FRs in a 1000m*1000m network; hence there is no dramatic difference of connectivity between CORPS and mRWP.

D. Mobility-assisted Gossip-based Broadcast

In this experiment, we evaluate the performance of mobility-assisted gossip-based broadcast protocol in Scen. 3 under CORPS and mRWP. Transmission range is set to 100 meters. The broadcast protocol performs as follows. Every node sends out a broadcast message every 60 seconds. A broadcast message is active in network for $TTS * 60$ seconds from the initial moment it is broadcast by source. A node n, receiving a message m, broadcasts m every 60 seconds afterwards, if m is still active and n does not hear any other nodes broadcast m during last 60 seconds in the neighborhood. We compare the broadcast performance in term of coverage (the percentage of nodes who receive broadcast messages when the messages become inactive) and message overhead (the percentage of nodes who broadcast in each 60-second period), by varying TTS. As we know, higher TTS increases the coverage by the cost of higher message overhead.

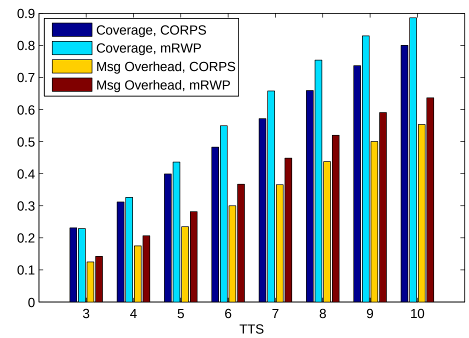


Fig. 14. Gossip-based Broadcast

Experiments show that coverage under CORPS is worse than that under mRWP; however, the message overhead is smaller for CORPS. This is because first responders usually cluster around attention events. Broadcasting repeatedly to the known neighbors does not help propagate the messages to other FRs outside the group. An efficient neighborhood management protocol can make the gossip more efficient by broadcast whenever a new neighbor is detected, especially an FR from a different group. Because first responders cluster around attention events in CORPS, messages are likely to be suppressed by neighbors, thus reducing the message overhead.

This experiment shows that, CORPS renders different performances of applications from mRWP. Therefore, evaluation of applications and routing protocols should be based on realistic mobility models for first responders, like CORPS.

V. Related Work

We summarize many mobility models in introduction. Here, we only focus on those bearing some similarity as CORPS.

Unlike random waypoint mobility model, users in CORPS do not move randomly inside the whole network. First responders are likely to move around attention events. Weighted random waypoint mobility model [16] has similar concepts of popular locations as attention events, where a user randomly selects a popular location based on popularity from a set of popular locations as the destination. Popular locations can be a library on campus and a grocery store in town. However, there are several differences between attention events and popular locations. First, *attending weight* prevents excessive gathering at a single event, which is impractical in closely collaborative emergency responding scenarios. However, a popular location can attract unlimited number of users. Second, events are often NOT globally visible. An event is visible only to those FRs who have detected it. This models the unpreparedness for incident operations. Third, events may occur and decease with dynamic lifetime. Finally, attention events mirror semantics of mission. How quickly first responders can solve an attention event determines how long they stay at the location. As more FRs commit to an event, the absolute time required to complete the event decreases. Moreover, first responders are moving in the confined attending zones of attention events.

[5] proposes a path calculation based on Voronoi Graph defined Pathways in presence of obstacles. People only move along pathways. However in rescue mission, there are no clear boundary for paths and FRs may traverse all the possible positions not covered by obstacles. Furthermore in CORPS, obstacles are extended to forbidden zones, which are more mutative than static obstacles.

Displace locations in microgroup are similar to reference points in [13]. Yet trajectory approximation algorithm for microgroup is simpler than that for groups of multiple people. In CORPS, first responders of the same role form a macrogroup. They only temporarily assemble around the attention events they are committed to. Otherwise, they move individually. In some sense, group relationship in CORPS is more dynamic. This is different from group concept in [13][4], where group members always move in close proximity, though groups may partition and merge at predefined time points.

VI. Conclusion

In this paper, we present CORPS, a novel mobility model for first responders in incident scene. It is tailored for mobility pattern featured with organization, collaboration and responsiveness. By accurately reflecting the operational logistics, CORPS enhances the fidelity of mobility models and renders more convincing simulation results for first responders.

In the future, we plan to collect mobility traces for firefighters in small-scale practice to validate our model.

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