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MASF: A novel priority based multi-agent framework for search and rescue

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Abstract. In this paper, a novel priority-based framework for a semi-autonomous multi-agent-based search and rescue mechanism is proposed. The framework proposes a novel multi-layered architecture consisting of multi-agents capable of target detection, role allocation, and connectivity based on access to resources. Four different operations have been proposed, namely mapping, searching, coordination, and information fusion. Three different roles for the agents have been proposed: mapper, searcher, and coordinator, where the mapper agent contributes to developing local maps. The searcher agent explores the local map for target detection and coordinator agent responsible for cluster coordination and communication inter-cluster, intra-cluster, and information fusion module. A novel concept of cell priority index (CPI) has been proposed to determine the level of damages and zone prioritization for a rescue operation. Two different novel indices, namely role suitability index and role weighting index, have been proposed to allocate roles among agents. The ad-hoc network model of the proposed system is evaluated for performance metrics under different mobility mechanisms in different propagation environments to suggest possible mobility approaches to be adopted for effective search and rescue mechanisms.

Keywords: *Multi-agents, search and rescue mechanism, cell priority index, mobility models, propagation environments*

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1. Introduction

In a Search and Rescue (SAR) scenario, it is essential to locate survivors efficiently and inform the rescue authorities immediately [1]. However, search and rescue missions for individuals trapped inside buildings are conducted by humans who are accurate in locating victims but inefficient in time constraints, causing decreases in survival rates for the individuals [2,3]. For an efficient method of locating and rescuing individuals, designing a human-centric semi-autonomous multi-agent system is essential. Moreover, due to unknown topology and attenuation in scattered structures, wireless communication among agents is not fully optimized. Again, semi-autonomous agents can only locate individuals and transmit locations to information fusion modules controlled by humans. As a result, it is necessary to design a structure for human-agent collaboration [4].

Moreover, it is necessary to consider mobility and propagation environments to have an efficient data retrieval mechanism. It is expected that ad-hoc network parameters will vary under different mobility and environment. In Random Direction (RD) model [5], agents choose a random direction, and after reaching the simulation boundary, pause for a specified time and then choose another angular direction (between 0 and 180 degrees). The Random Waypoint Mobility model (RWP) [6] extends Random Direction (RD) with pulse time intervals during direction changes. In the Gauss- Markov (GM) mobility Model [7], each agent is initially assigned with a speed and direction, updated according to GM equations at fixed intervals.

A probability matrix is used in the Probabilistic Random Walk Mobility model (PRW) to determine an agent's location in the next time step. In the Nomadic Community Mobility model (Nordic), each agent roams around a defined reference point, and with changes of the reference point, orientations of the agents in the group change. Agents' new directions are confined in the newly defined area by the reference point. The Reference Point Group Mobility Model (RPG) allows agents' movements based upon the direction of a reference center of the group. The reference center characterizes the movements of its corresponding group of agents. Each agent's orientation is based on its reference point, where the logical reference point's movement is based on the group movement [7]. However, few suggestions for choosing a mobility model for search and rescue scenarios indicate the scope of research.

Several studies propose multi-agent-based approaches to build an effective model for search and rescue. Researchers in [8] propose an agent-based model with distributed, cooperative, and highly reactive agents with multi-hop information sharing features. In [9], researchers propose a cooperative agent-based wireless sensor ad-hoc network model. However, the assumption of having a stable communication link among agents limits the applicability of the proposals in disaster scenarios [10]. Researchers in [11] propose a multi-layer and combined framework for multi-agents. However, optimization in multi-agents is yet to be efficient. In [12], the minimization of the average duration of detecting targets is proposed. However, an efficient target detection algorithm with a confidence level is yet to be proposed. There are still scopes for improvement in designing an efficient search and rescue model.

This paper proposes a novel architecture for a layered semi-autonomous multi-agent-based search and rescue mechanism, Multi-Agent Search Framework (MASF). It is proposed that each agent have a priori map of possible targets that can be updated after each search. Target detection mechanisms and role allocation for agents based on a suitability function are also proposed to have an efficient searching and informing scheme. A novel concept of Cell Priority Index (CPI) is also proposed to determine rescue queues. Two novel concepts of role suitability and role weighting index are proposed in this paper. Different mobility models and propagation environments are tested to find a realistic mobility model for MASF. The rest of this paper is organized as follows. In section 2, the proposed MASF framework is explained. In section 3, the results on different mobility and propagation models are presented, and section 4 concludes the paper with future implementations.

2. Proposed MASF framework

2.1. Framework overview

The proposed MASF framework consists of an opportunistic wireless mesh ad-hoc network consisting of four layers of operations: map, search, coordination, and information fusion. A group of homogeneous agents was proposed to perform tasks of the first three layers. Agents are defined, in this paper, as agents having some basic parameters such as the capability of sensing, minimum processing ability to decide based on the installed algorithm, the capability to transmit and receive signals. Each agent is assumed to have sensory modules such as GPS, gyroscopes, laser scanners, onboard cameras, ultrasound distance mapper, and gas sensors. The agents are assumed to be mobile in a mesh topology and have access to wireless communications and transmit and reception of data. It is assumed that each agent is capable of localizing itself and detecting targets. Every agent can send information to other agents within its range. The information fusion module is proposed to be semi-autonomous and operated over the disaster area, and assumed to send and retrieve information from agents. It is responsible for performing information fusion and sending new information to the ad-hoc network. Based on the priority index, the information fusion module prioritizes the rescue queue, i.e., which cell to rescue first. The information fusion module then sends new information such as a new map to the agents based on the information analyzed. Figure 1 shows the stages of the proposed MASF framework.

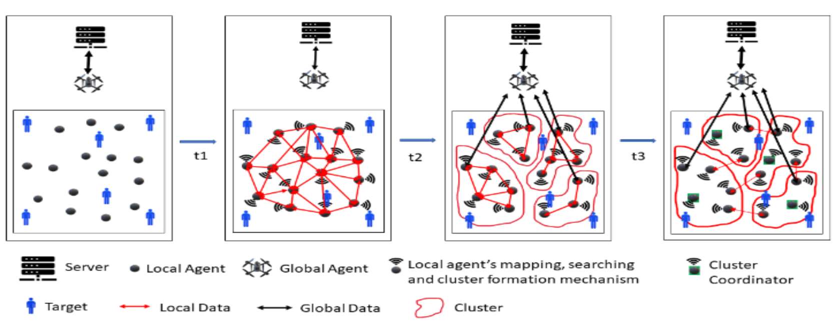

Figure 1: Four stages of MASF

From Figure 1, it can be seen that, in stage 1, the agents are distributed randomly in the disaster area and have no connection with the information fusion module. In stage 2, the agents start mapping the surroundings and searching for targets. In this stage, the agents also start transmitting and receiving data for forming clusters based on link strength, position, and energy. In stage 3, the agents form clusters and start transmission and reception of data regarding target findings. In stage 4, the accumulated data are sent to an information fusion module for analysis and, at the same time, receive command and updated information such as map, cell priority, and validation commands from the information fusion module.

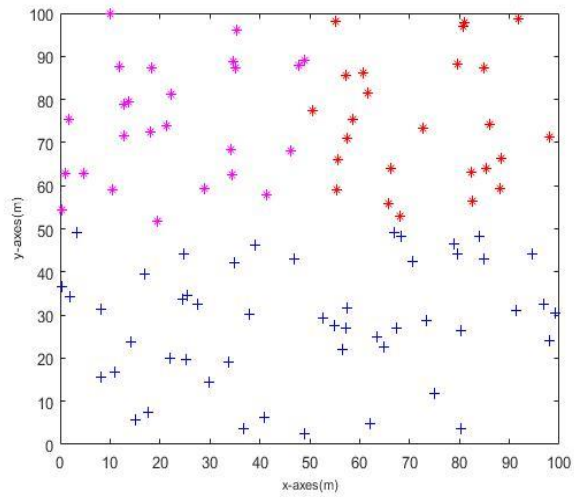

Figure 2. Simulated agents in a 2D disaster area

2.2. Searching mechanism

It is assumed that X homogeneous mobile agents are dispersed in Z regions having Y targets. The agents are provided with a probability map containing probabilities of the location of targets which is updated dynamically based on previous steps and information from other agents in a region or the information fusion module. The agents are dispersed in a disaster site as a group and are initially assigned with a mapper role. After entering the site, agents form teams of at least three agents with different roles to have efficiency. Based on the mobility model and clustering scheme, the agents are then set to map, search and locate targets in different regions. Each region can be regarded as a composition of uneven cells, and each agent team will search each cell for targets. Finding a target in specific regions increases if no target is found in the previous regions. Let x_k be the initial state vector denoting the location and orientation of an agent, u_k be the action vector of the agent denoting the action taken by the agent based on information from coordinator to drive at a state vector x_k, m_i be a vector denoting the location of i^{th} target, m be the local map and z_{ik} be the information acquired from z_k^{th} location and i^{th} target, then the state and time update mechanism can be derived from [13],

$$x_k = P(x_k, m \mid z_{0:k}, u_{0:k}, x_0) \quad (1)$$

$$P(x_k, m| \, z_{0:k-1}, u_0, x_0) = \int p(x_k| \, x_{k-1}, u_k) p(x_{k-1}, m| \, z_{0:k-1}, u_{0:k-1}, x_0) dx_{k-1} \quad (2)$$

The probability of finding a target for an agent can be expressed as [14],

$$P_{z_i}^{t_j} = \frac{1}{\Delta} \int_R^{R+\Delta} dR' \left[1 - \prod_{i=0}^{l} \left(1 - p\left(\frac{R\prime + i\Delta}{R_0}\right)\right)\right] \quad (3)$$

Where $P_{z_i}^{t}$ is the probability of finding a target in z_i^{th} region in t_j time, Δ is the distance between an agent and a target, R and R' are the searching range of an agent and the relative range of the agent during mobility, l is the arbitrary limit of acceptance of the false alarm, and R_0 is the range for unity signal to noise ratio of the agent. Suppose each agent is equipped with q sensors, and $f(d_r)$ is the accuracy function of r^{th} sensor, which gives probability as output with ζ_r confidence, the probability of accurate detection of the target, modified from [15], can be expressed by the following equation,

$$P_d^{t_j} = \frac{\sum_{r=1}^{r} \zeta_r (f(d_r))}{\sum_{r=1}^{r} \zeta_r max(f(d_r))} \quad (4)$$

2.3. Cell priority index

In this paper, a cell priority index (CPI) for efficient queuing of target rescue is proposed. The CPI for all cells can be formed by taking $P_{z_i}^{t_j}$ and $P_d^{t_j}$ from $x_i; i = 1, 2.... X$ agents. The coordinators receive the indices from the searcher agents and broadcast them to the rescue authorities. From equation 3 and 4, the CPI_{z_i} for z_i^{th} cell is defined as,

$$CPI_{z_i} = \sum_{t=0}^{t} \sum_{i=0}^{x} \left(P_{z_i}^{t} . P_d^{t}\right) \quad (5)$$

CPI is calculated in the information fusion module and regularly updated from the information received from the agents. The updated map with CPI is then sent to the agents for validation.

2.4. Connectivity and role allocation

The MASF model introduces a modified function for the role allocation mechanism inspired by [16]. Three different interchangeable roles for the agents are proposed in this model, namely mapper, coordinator, and searcher. The role of a mapper agent is to navigate and build a map of the surroundings. The map is updated when information from other mappers via members or coordinators is provided. A searcher searches the explored region of the mapper for targets. It is provided with a prior probability map of the target location, and it updates the map after a region is searched. A coordinator in a region is connected to most of the agents and is responsible for inter-group and intra-group communications to ensure the completion of tasks. An agents suitability to be assigned with a role within a region is based on the sum of the weighted suitability for the agent to perform specific tasks to be done by that role, i.e., an agent can become a searcher agent during a role check when it can perform the tasks to be

done by a searcher agent.

Let $f\left(n_{E_i}\right)$ energy, $f(\sigma_i)$ denote wireless link strength among agents, $f\left(S_q\right)$ denote the number of active sensors needed, $f(L)$ denote the function of distance and $f(X_i)$ denote the number of agents in i_{th} cell, then the weighting index of an agent, Ω_i, is defined as,

$$\Omega_i = \frac{f(\sigma_i)+f(S_i)+f(L_i)+f(X_i)}{f\left(n_{E_i}\right)} \quad (6)$$

Assume that in a specific time range of t_i and t_j let $\kappa(\tau_i)$ be denoted as the suitability parameter of an agent to perform τ_i^{th} task of a role, then the suitability κ for the role is defined as the product of suitability parameter and weighting index Ω_i,

$$\kappa = \sum_{i=0}^{n} \kappa(\tau_i)\Omega_i \quad (7)$$

Assume the connectivity among cells can be represented as a bipartite graph $G_\mu = \left(V_\mu, E_\mu\right)$ where there is at least one agent in V and at least one path between the neighboring cells. Let $V_\mu = v_1, v_2, v_3 ..... V^{x_i}$ where x_i denotes the number of agents in i^{th} cell and let $E_\mu = e_1, e_2, e_3 ...... e_m$ where m denotes edges. Then the adjacency matrix A_μ for G_μ can be denoted as,

$$A_\mu = \begin{cases} 1, & If \text{ the } path\ exists\ between\ v_i\ and\ v_j \\ 0, & otherwise \end{cases} \quad (8)$$

Cluster formation in the proposed model is based on distance and energy function in a cell inspired by [17]. At first, an agent searches for neighbors and updates neighbor list N_L. After updating N_L, the agent calculates Ω and κ. It then transmits the value of κ to the neighbor agents. If its κ is more significant than any agents in N, it is allocated the role of coordinator. Otherwise, it is assigned with a searcher role or mapper role based on κ value. The role check procedure is assumed to occur periodically. The intra-cluster connection is assumed to be an ad-hoc network.

3. Results and discussion

The following segment discusses the simulation consideration, propagation mechanisms to be evaluated, mobility models, simulation setup, and performance evaluation of the proposed model.

3.1. Simulation consideration

Some simulation considerations have to take into account to simulate the ad-hoc network portion of the proposed model. In a disaster area, there is no way to predict the propagation environment. It is necessary to evaluate the model under various propagation environments and mobility models to have maximum efficiency. Two Ray Ground propagation model [18] is useful when there is a LOS path as it depicts the case of ground reflected signals to be received by a receiver. The received power of the model can be defined as,

$$P_r = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{9}$$

Where h_t and h_r are the transmitter height and the receiver height $,gt\ and\ gr$ denote the gain of transmitter and receiver antennas, respectively, while d is the distance and L is the system loss. Shadowing propagation [19] assumes that the average receive signal attenuates logarithmically concerning distance. The model can be defined, with d denoting distance and d_0 denoting initial distance, as,

$$\left\{\frac{P_r(d)}{P_r(d_0)}\right\}_{dB} = -10\beta\left\{\frac{d}{d_0}\right\} \tag{10}$$

β is a Gaussian random variable depicting environmental influence, which has zero mean and standard deviation of σ_{dB} also denoted as a shadowing deviation. Nakagami propagation [20] offers a more realistic simulation environment of wireless communication as it can predict free space to the fading the environment of the disaster area. The Nakagami probability density function is defined as,

$$f_D(d) = \frac{2m^m d^{2m-1}}{\gamma(m)\phi^m}\epsilon^{\frac{-md^2}{\phi}}, d \geq 0, m \geq \frac{1}{2}, \phi \geq 0 \tag{11}$$

where $\gamma(.)$ is gamma function, and m and ϕ are shape and scale parameters, respectively.

3.2. Simulation setup

The ad-hoc network model of the proposed architecture is evaluated through simulation for performance parameters, namely throughput, overhead, active agents and dead agents per round, residual energy, and normalized energy loss per round. Each parameter is investigated under different mobility models mentioned in the previous section. Energy investigation is done under a generalized scenario. Three different cases of the propagation medium, namely Two Ray Ground, Shadowing, and Nakagami Propagation mechanism, are investigated for each parameter with mobility models. The discrete-event simulator NS2 (version 2.35) has been used to simulate the ad-hoc network parameters of the proposed model. To create the topology and mobility models, BonnMotion ($v3.0.1$), a Java-based mobility scenario generation tool, is used. For calculating energy consumption, MATLAB (r2017a) is used.

In NS2, an area of $600\ m^2$ is considered. IEEE 802.11 is considered the MAC type, while AODV is considered the routing protocol of the proposed model in simulating Wi-Fi and Bluetooth, while IEEE 802.15 is considered for simulating Zigbee. Bandwidth is limited to 2.4 GHz to mimic the ISM Band. Transmission speed has been varied from 250 Kbps to 64 Mbps to mimic the characteristics of Wi-Fi, Bluetooth, and Zigbee, which are close candidates for the proposed model. The antenna for each agent is set to 0.2 meters above their body.

For Two Ray Ground propagation mechanisms, default NS2 parameters with large packet sizes set to 512 bytes and small packet sizes set to 5 bytes have been used. For the shadowing propagation mechanism, β is set to $4.5\ dB$ with σ_{dB} of 7. For the nakagami propagation mechanism, γ is set to 2, γ_d is set to 200, and fading parameter m is set to 1. The maximum contention window is set to 31, while the maximum is set to 1023. Short Retry Limit (SRT) is set to 4, and Long Retry Limit (LRT) is set to 7 to mimic Wi-Fi characteristics. Initial energy for each agent is set to 100 Joules, while energy loss per transmission is set to 0.6 Joules and 0.3 for the reception. The maximum speed for each agent is set to $2.5\ ms^{-1}$. Antenna gain for both receiver and transmitter is set to 4 db. The number of agents is chosen to be 100.

3.3. Simulations and results

It is essential to define the performance parameters used to evaluate the scenarios to visualize the results better. Throughput denotes the cumulation of total data received at the receiver successfully at a unit time and is measured in Kbps in the experiments. The overhead ratio denotes the ratio of channel/network control packets and data packets. It is expected that throughput will be higher, and routing overhead will be lower to have an efficient communication network.

3.3.1. Two ray ground propagation

It is expected that with the increase of transmission speed, the overall throughput of all mobility models will increase. Figure 3 shows that Reference Point Group Mobility shows higher throughput than other mobility models in the LOS path. Figure 4, Figure 5, and Figure 6 show that Random waypoint has the maximum overhead compared with another model. In RWP, agents move randomly with a uniform speed and direction, and its highly unpredicted nature creates varying distances among agents. As a result, overall overhead increases as control messages for link build-up and cluster head selection increases.

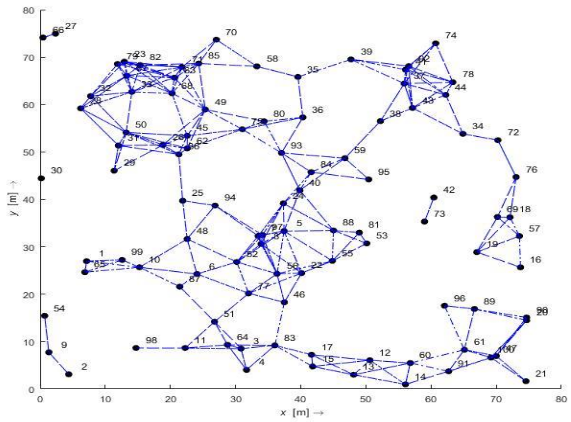

Figure 3: Connectivity with 100 agents

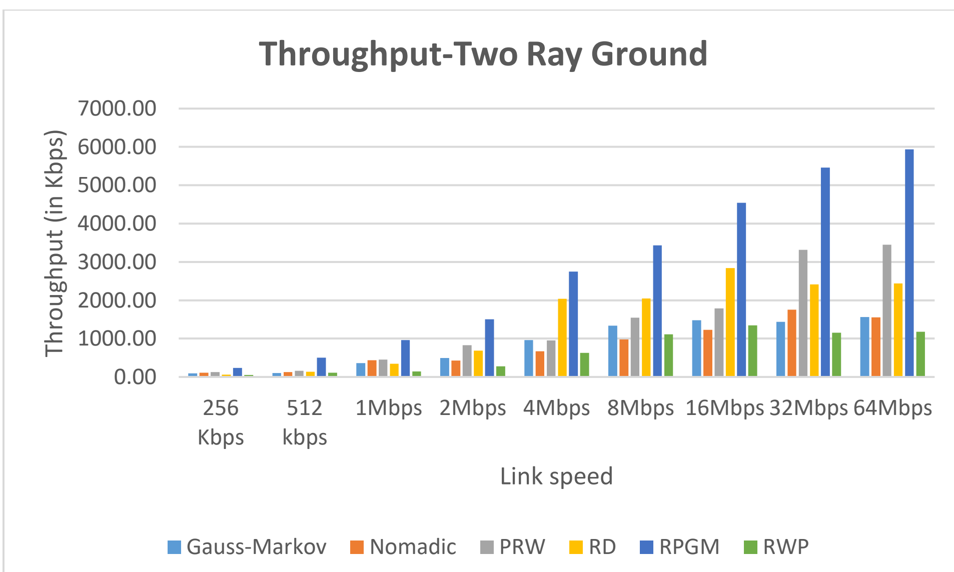

Figure 4: Throughput- two ray ground propagation

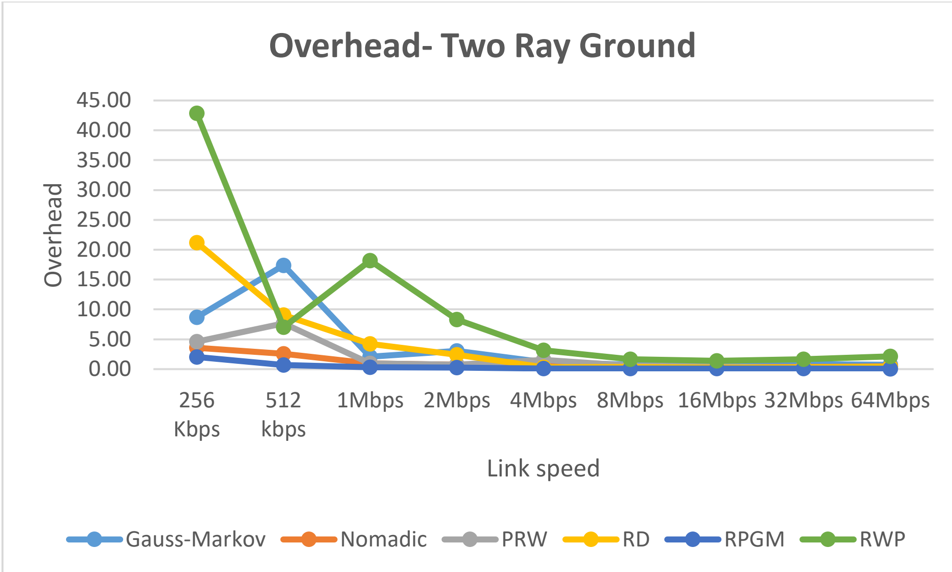

Figure 5: Overhead- two ray ground propagation

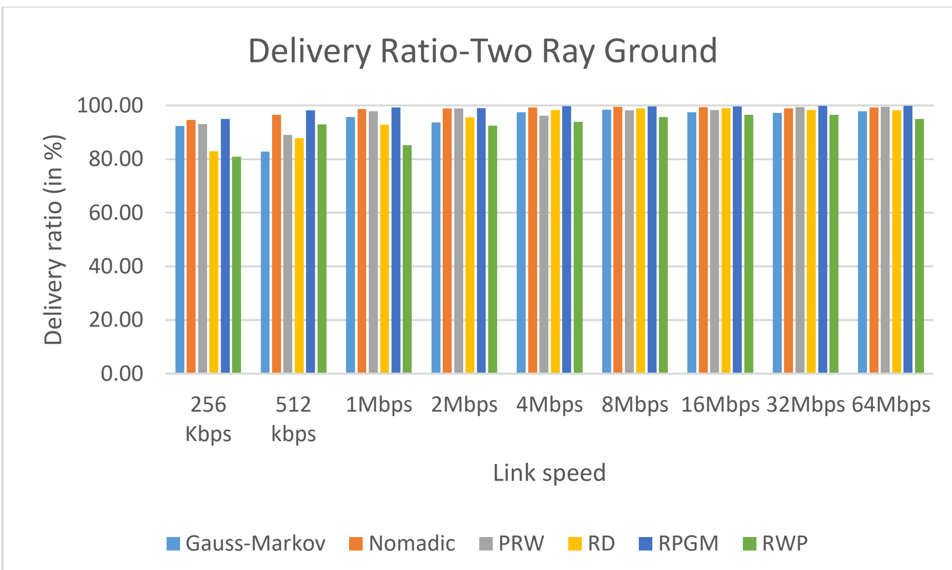

Figure 6: Delivery ratio- two ray ground propagation

3.3.2. Shadowing propagation

Due to the nature of Shadowing propagation, it is expected that not all mobility models will have excellent throughput. Figure 7, Figure 8, and Figure 9 show that RPGM shows better throughput than the other models. In RPGM, agents in a region follow a group leader, and communication among group members is more ensured as they lie within the range of the leader. From Figure 7, it can be seen that the Gauss Markov mobility model has the highest overhead ratio and RPGM has the lowest. This is also because of the topology and mobility characteristics of the two models.

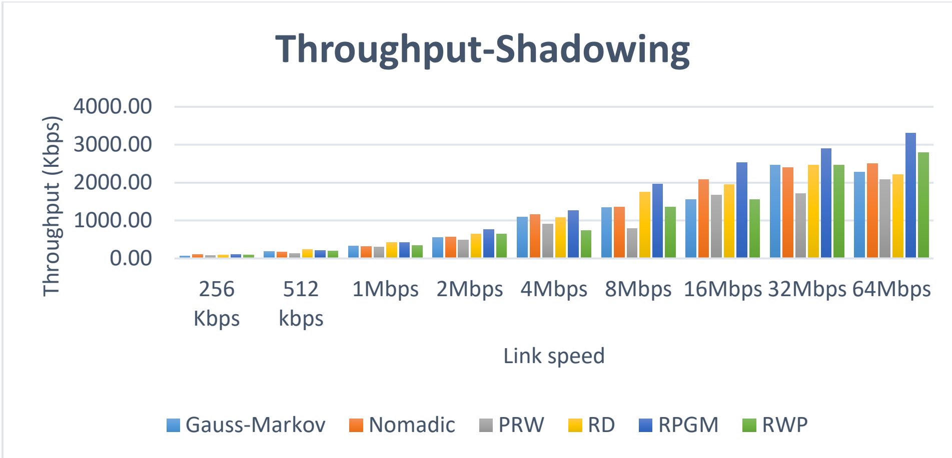

Figure 7. Throughput- shadowing propagation

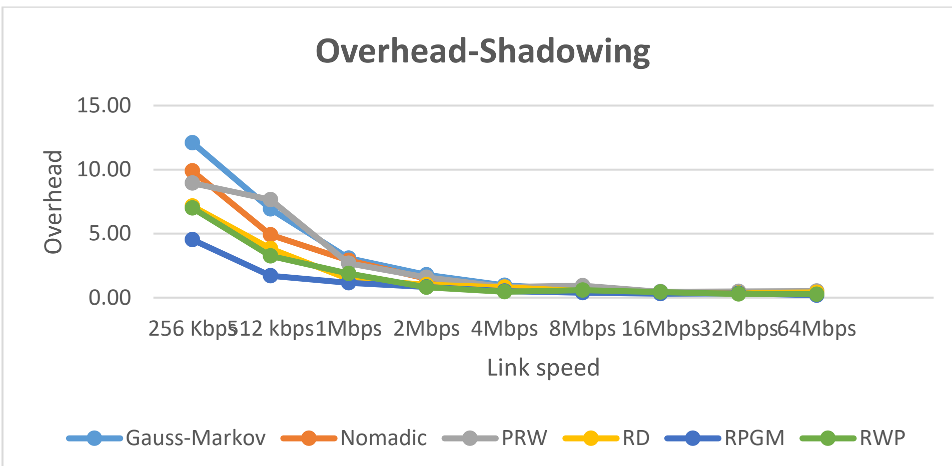

Figure 8: Overhead- shadowing propagation

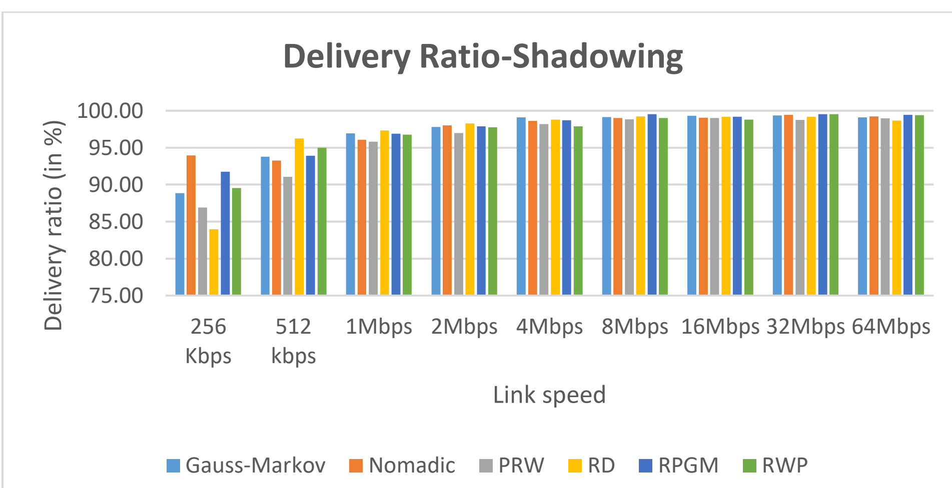

Figure 9: Delivery ratio- shadowing ground propagation

3.3.3. Nakagami propagation

Nakagami propagation mechanism depicts the most realistic environment of search and rescue. It can be seen from Figure 10 that the throughput of different models varies under different transmission speeds while RPGM achieves better value. It can be seen in Figure 11 and Figure 12 that overhead ratios for all models are nearly the same for varying transmission speeds. However, Nomadic mobility shows the worst overhead ratio as all the agents follow a single leader, and connectivity and data transmission to the far-end agent require more control packets.

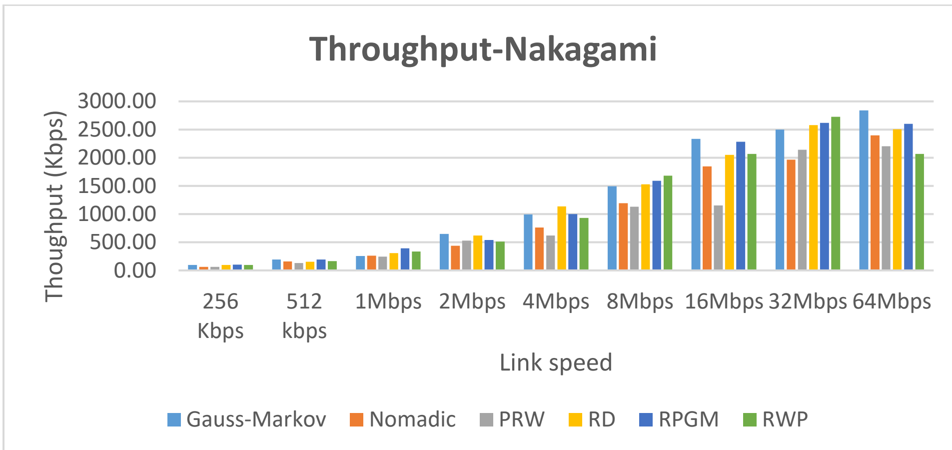

Figure 10: Throughput- nakagami propagation

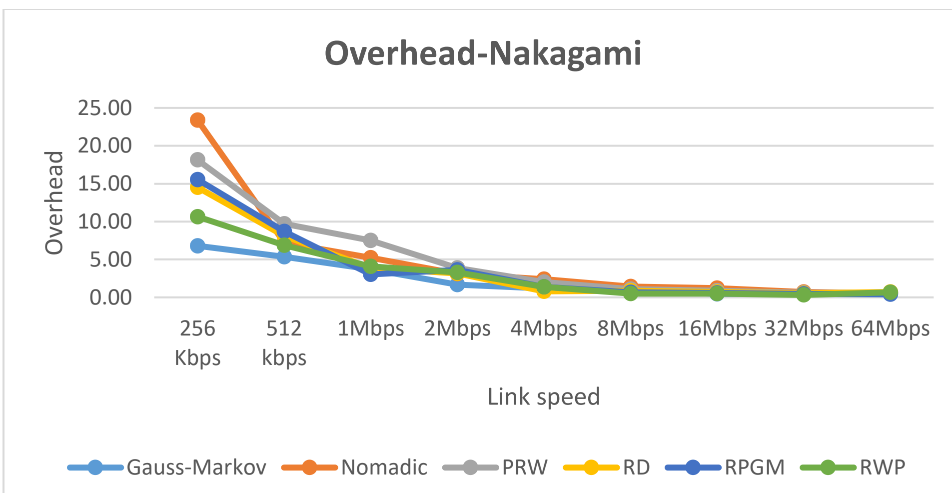

Figure 11: Overhead- nakagami propagation

3.3.4. Energy consumption

Energy consumption in the search and rescue mechanism is an important parameter to be considered. It can be seen from Figure 13 that with continuous transmission rounds, alive agents, i.e., agents with energy, decrease with each iteration of the transmission. With every iteration, agents waste energy on the transmission of data packets and control packets. As mentioned above, the number of dead agents increases as continuous transmission and re-transmission occur, as seen in Figure 14. Figure 15 and Figure 16 conclude that residual energy and normalized energy loss per round depend on the active agents in the ad-hoc network and decrease the number of agents' decreases.

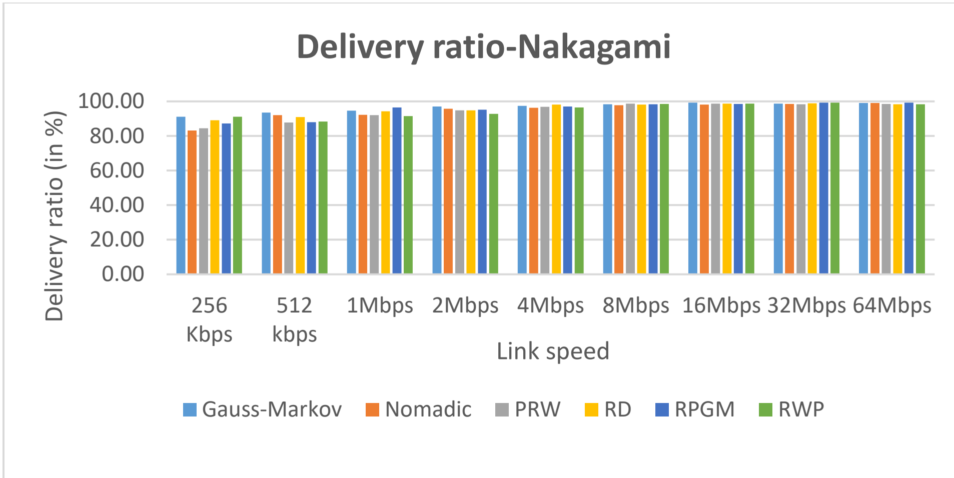

Figure 12: Delivery ratio- nakagami propagation

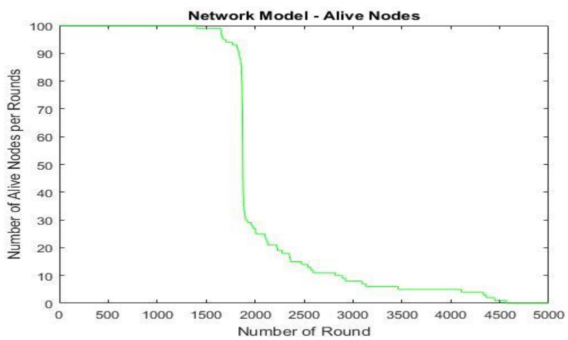

Figure 13: Alive agents per round

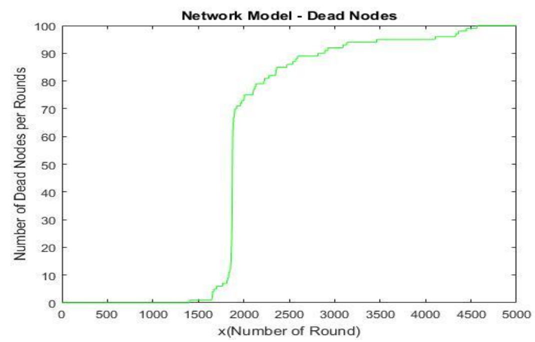

Figure 14: Dead agents per round

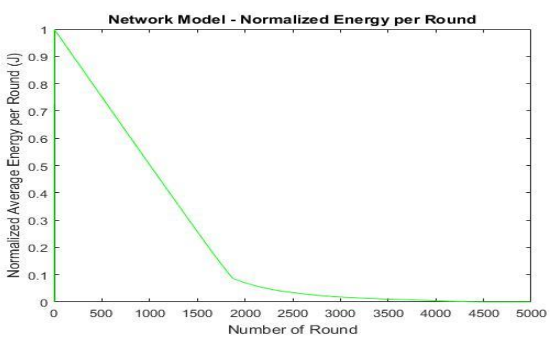

Figure 15: Residual energy per round

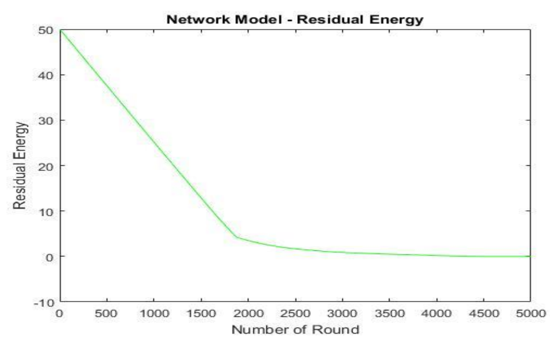

Figure 16: Normalized energy per round

4. Conclusion

In this paper, a priority-based multi-agent search and locate scenario, MASF, is proposed. In this model, CPI is proposed to determine the rescue priority of the specific regions. Two novel concepts, namely the role suitability and role weighting index, are proposed for effective role allocation. The model's ad-hoc network model is evaluated for different mobility models and different propagation environments in the experiment section. It can be seen that reference point group mobility is a better candidate for search and rescue mechanism using multi-agent cooperation. Immediate future extension of this work is to include a machine learning algorithm for the information fusion module and agents for better information fusion and prediction of maps for efficient target detection. Another extension of MASF is to develop a working model to evaluate the framework against real case scenarios.

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