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Investigation on communication aspects of multiple swarm networked robotics

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Abstract: Swarm robotics is an emerging field of robotics and is envisioned to play a vital role in surveillance and search/rescue operations. Most of the existing works on swarm networked robotics address the problem of formation movement or the communication aspects within a swarm. However, none of the existing works consider multiple swarms. Even for the case of single swarms, researchers use unrealistic assumptions with respect to communication, leading to unrealistic results. In this paper, we evaluate the performance of multiple swarms considering realistic assumptions with respect to communication. To the best of our knowledge, it will be the first time where the performance is evaluated for the case of multiple swarms while considering realistic assumptions with respect to communication. Our simulation results shed light on the roles of three different types of communication associated with multiple swarms with respect to multiple performance metrics.

Key words: Networked swarm robotics, formation movement, communication, pattern formation

1. Introduction

Swarm robots consist of large number of simple robots that are capable of sensing and actuating in a real environment. Inspiration for swarm robotics comes from the observation of insects like ants, bees, and flocking birds [1]. Swarm robotics works in a distributed fashion. The self-organization feature of swarm robotics is one of the key features that facilitate achieving fault tolerance, high robustness, and scalability [2]. Swarm robotics is a relatively new and challenging field in which multiple robots coordinate with each other based on local interactions. To accomplish any task in swarm robotics, multiple robots coordinate and interact with each other [3]. Complex tasks are divided and distributed among different nodes effectively, which is the basic motivation behind using swarm robotics. This allows multiple robots to perform a number of tasks simultaneously [4]. There are many applications of swarm robotics, like search and rescue, surveillance, detection of mines, and marine environment monitoring [5–7].

Networked robotics is an area that combines robotics and networking technologies. Multiple robots work together to accomplish a task and through a network they communicate with each other and the user [3]. In networked robotics, multiple robots are connected through a wired or wireless network to share information and achieve their assigned tasks. However, due to the limited communication range, it is often important for a robot to maintain close proximity to teammates within the group while moving in the environment [4]. Swarm robots use different wireless communication devices to communicate/share valuable information with their neighboring

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robots [8]. Moreover, they are equipped with multiple wireless technologies that can be used for different types of communications [3]. For instance, a swarm robot can use Bluetooth for short-range communications and Wi-Fi for communication over relatively larger distances [9].

In swarm networked robotics research, two main research problems are addressed by researchers. The first one is formation movement and the second is communication. For the completion of the assigned task, formation movement of a swarm plays a key role. Formation movement is one of the specific cases of collective movement, where a robot is required to travel a fixed distance at an angle that is relative to other robots in the group [10,11]. In swarm robotics, pattern formation is the ability of the robots to arrange themselves in the desired relative positions according to their goal [12]. Examples of pattern formation in nature are fish schooling, birds flocking, and ants making chains [4].

The second problem is related to communication. The communication can be of two types. The first type is communication between the user and networked swarm robots, known as user-to-swarm communication, and the second type is communication between robots within the swarm, called intraswarm communication. These problems are related, and one affects the other and vice versa [13].

The previous literature considers a single swarm only and addresses the challenges associated with it. However, there are many scenarios in which a single swarm is not enough to accomplish a task. Our work focuses on the environments in which multiple swarms are needed in order to accomplish a task. Considering multiple swarms makes pattern formation and communication problems even more challenging. The formation movement in the case of multiple swarms must ensure not only that the multiple swarms accomplish the assigned tasks but that they also stay connected with each other and with the user. The second problem is associated with the communication. Communication under environmental constraints is a challenging task in swarm networked robotics consisting of even a single swarm. Taking multiple swarms into account makes the communication problem even more complex. In the case of a single swarm, two types of communication should be taken into account, i.e. user-to-swarm communication and intraswarm communication. However, in the case of multiple swarms, interswarm communication also plays a very crucial role. Interswarm communication refers to the communication that takes place between multiple swarms. Generally, not all the swarms in an area are within communication range of the user; therefore, if a user wants to relay some new information to all the swarms, interswarm communication comes into play. In the literature, the communication aspect within swarm networked robotics is considered at an abstract level and most researchers consider unrealistic assumptions. For example, in some works, it is considered that all the nodes of swarms are always within communication range of the user. Such assumptions lead to unrealistic results and there is a need to consider a realistic communication model for evaluation with respect to different performance metrics for getting more realistic results. The focus of our research is to evaluate the performance of multiple swarms while considering realistic assumptions with respect to communication. To the best of our knowledge, it will be the first time when performance is evaluated for the case of multiple swarms while considering realistic assumptions with respect to communication.

The rest of the paper is organized as follows. Section 2 explains the literature review related to swarm network robotics. The performance evaluation is presented in Section 3. In Section 4, simulation results are discussed. Conclusions and future work are discussed in Section 5.

2. Related work

Most of the existing research on swarm networked robotics addresses two research problems known as formation movement and communication. Most of these works consider only one problem at a time. Below, we explain the most recent works addressing these problems and also elaborate how our work is different from these works.

In [14], the authors proposed a hybrid hierarchal/mesh network topology to send commands to various robotic swarms. In this work, a slave agent takes information from a master agent and forwards the commands. The problem with the network is that it breaks the swarm pattern. In this work, for communication the XBee-PRO modem is used, and it is an assumption that the swarms must be connected all the time. Loss of one of these master agents or nodes disrupts all communications so the system is not robust. The basic underlying assumptions, such as all swarms being connected with each other all the time, make their work different from our work.

In [15], the authors proposed an approach called dCRoPS that allows a swarm of robots moving towards their goal while avoiding collisions with dynamic and static obstacles. Scalability is achieved by a well-organized arrangement of probabilistic roadmaps to deliver global path planning. A potential field is used to guarantee that the swarm travels in cohesion. The major focus of this work is efficient formation movement of the nodes within a swarm. The fact that this work considers a single swarm only and does not take into account multiple swarms and realistic assumptions on communication makes it different from our work.

In [16], the authors proposed a new network routing concept. When robots in a swarm move from source to a target goal, the proposed scheme maintains the routing table and saves the results about distance with respect to the target. By using the routing table, the robots reach their target goal. In this work, it is assumed that all nodes of the swarm are connected all the time. Moreover, their work focused on communication for navigation and they just considered a single swarm for performance evaluation.

In [17], a node-mapping algorithm was discussed to determine the node association among the arbitrary initial topology and the particular desired topology. A tree is formed on the primary graph such that the node movement necessary in topology reformation is minimized and the routing algorithm proposed in [16] is used to identify how the preliminary graph can be transformed into the final graph. This work, also like [16], is based on a single swarm and user interaction with swarm nodes is also neglected.

In [18], the authors discussed an algorithm that solved the problem of transition of the system from one topology to another with different network configurations and to maintain the network connectivity. This algorithm uses the concepts of prefix labeling and prefix routing. The researchers assumed that all nodes have knowledge about their final network topology. The issue here is: if in an initial graph any robot loses its position, then how will the nodes achieve the final topology? The authors considered a single swam only and also did not take into account user-to-swarm interaction.

For multirobot systems, researchers address the issue of connectivity maintenance for ensuring that none of the robots lose connectivity from the rest of the group. In [19], for single integrator agents, a new connectivity maintenance control strategy based on the decentralized estimation of the algebraic connectivity of the communication graph was proposed. The communication graph is split in the case of disconnection, but later on, the researchers extended this control strategy, explicitly taking into account the dynamics of real robotic systems. In the proposed work, all the nodes stay connected with each other during communication. This work considers communication but uses the unrealistic assumption that all the nodes stay connected. Moreover, unlike our work, this work does not consider the case of multiple swarms.

In [20], the authors worked on ensuring that the group of robots stays connected in the presence of a restricted communication range and limited sensing when some purpose is achieved. Due to this, the problems of formation control and rendezvous are particularly explored by considering the Laplacian of the graph based on nonlinear feedback control law. In [20], connectivity of nodes in graph was a major concern and the authors did not consider a single swarm and did not consider user-to-swarm interaction.

To control a group of agents with constraints on limited sensing and network connectivity, each agent is assumed to have knowledge about the environment or limited sensing capabilities and limited communication capabilities with nearby agents. To show the effectiveness of the navigation function, two approaches of formation control and rendezvous were developed in [21]. In this work, the authors were able to achieve convergence to a desired configuration and maintenance of network connectivity by using a decentralized navigation function approach that uses only local feedback information and there radio communication was used. By using a local range sensor, an advantageous feature of the developed decentralized controller is that no interagent communication is required. That is, the goal is to maintain connectivity so that radio communication is available when required for different mission/task scenarios, but communication is not required to navigate. This work also assumes that the communication links stay connected all the time, but in contrast, in our work we consider that the nodes do not stay connected with each other all the time.

In [22], the authors considered a realistic communication model by introducing a probability of packet loss during communication. The focus of their work was to propose an extrapolating method with reduced computational cost but high estimation accuracy for the position estimation of swarm robots. However, their work was confined to a single swarm only and focused more on efficient position estimation of robots in the presence of packet loss. Moreover, from the communication perspective, just intraswarm communication was considered.

In [14–18], the focus of the authors was on the formation movement problem by considering a single swarm only, while in [19–22], the authors focused on the communication aspects of swarm-networked robotics by considering a single swarm only. Moreover, from the communication aspect, just the intraswarm communication was considered in all of the mentioned works. Our work is distinguished from all the mentioned works because we consider multiple swarms and evaluate the performance by considering three different types of communications associated with multiple swarms. To the best of our knowledge, this will be the first time when multiple swarms are considered and the performance is evaluated using the three different types of communications associated with multiple swarms.

3. Performance evaluation

In this section, we discuss different assumptions that were taken into account while doing the performance evaluation. We also discuss the simulation setup and the different performance metrics used for evaluating performance.

3.1. Network model

We consider mobile robotic nodes present at the origin at the start of the simulation at time $t = 0$. At time $t = 0$, for each swarm, a different goal is generated randomly. It is a requirement that at least one swarm must always stay in the range of the user in order to receive and propagate the information received from the user. To ensure this, one goal is always generated such that its coordinates fall within the range of the user.

3.2. Communication model

Figure 1 shows three types of communication that are considered while considering multiple swarms.

- User-to-swarm communication
- Intraswarm communication
- Interswarm communication

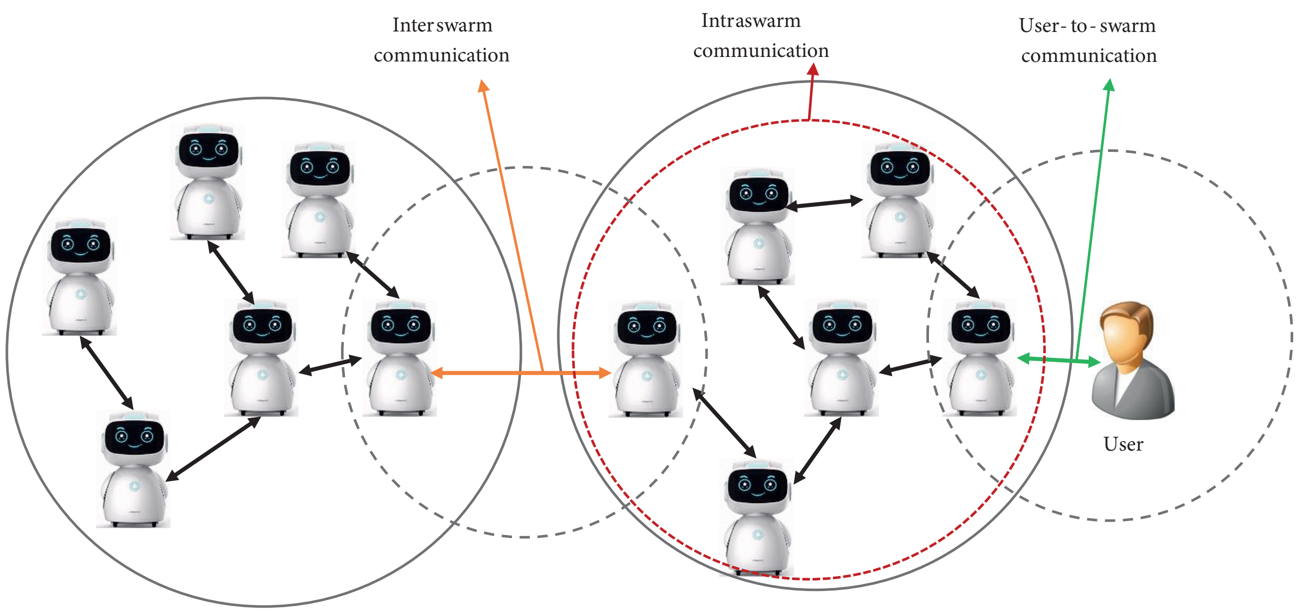

Figure 1. Three different types of communication.

In user-to-swarm, communication that takes place between the user and the corresponding swarm and interswarm communication that takes place within different swarms. Wi-Fi is used for both user-to-swarm and interswarm communication. In order to simplify communication, a radio fading model [23] is used. According to the radio fading model, the received power at the receiver decreases as the distance between the sender and receiver increases. As a result, the probability of receiving a packet successfully decreases as the distance between the sender and receiver increases.

For intraswarm communication, Bluetooth is used. For Bluetooth communication, real communication traces available from [24] were used.

3.3. Mobility model

All the robots move according to the Reference Point Group Mobility (RPGM) model. In the RPGM model nodes are divided into groups (swarms). In the RPGM model nodes randomly move around the reference point or follow the leader [25]. A similar mobility model was also used in [26]. The nodes in a swarm move towards the goal in the form of an ellipse such that all of the nodes within the swarm always stay connected, i.e. they stay within each other's Bluetooth communication range. Once a swarm visits a location in the simulation area, it cannot visit the same location again. Due to the dynamic environment the distance between swarms increases or decreases with respect to their movement. At time $t = 0$, all the swarms are at the origin and the respective goals for each swarm are chosen randomly. Once the goal is set for a swarm then all the nodes of the swarm move toward its goal. Once all the nodes of a swarm reach the location of the goal then that goal is moved to a new random previously unvisited location. The simulation is run until 90% of the simulation area is covered.

3.4. Simulation setup

For simulations, we used MATLAB, which is a multiple-worldview numerical computing environment. The reason for using MATLAB is its flexibility and wide popularity among the research community. The simulation setup relies on numerous parameters, e.g., size of simulation area, number of robots in a swarm, number of swarms, communication range, number of goals, goal position, origin, and robot distribution. In the simulations, we considered three swarms, each containing four robots. All the robots move according to the RPGM model. We have set the communication range of user-to-swarm, intraswarm, and interswarm communications according to the technologies used. For intraswarm communication, we have set 10 m, which is a common Bluetooth Class 2 transmission range. For Bluetooth communication, real communication traces of Bluetooth obtained from the experiments done in [24] are used. For user-to-swarm and interswarm communication, Wi-Fi 802.11g is used. The Table shows different simulation parameters of our simulation environment.

Table. Simulation parameters.

Parameters	Specification
Number of swarms	3
Number of nodes in each swarm	4
Number of goals	3
Communication	Wi-Fi (radio fading model) Bluetooth (real connectivity traces)
Nodes' distance within a swarm	< 10 m
Simulation area	3000×4400 m^2
Total number of cells	$20 \times 16 = 320$

3.5. Performance metrics

In our work, the following metrics were used for performance evaluation.

- Success ratio: Success ratio is the ratio of the number of packets successfully received and the total number of packets generated during simulations.
- Total number of packets received successfully: The total number of packets received successfully is the count of total number of packets received successfully during simulations.
- Average delay: The average delay is computed by taking the average of delay experienced by all packets generated during simulations.

All the simulation results were computed by taking an average of 10 different simulation runs.

4. Simulation results

Figure 2 presents the average success ratio with respect to simulation time. It is evident that the success ratio stays at 1 until 150 simulation seconds. The main reason behind this is that until 150 simulation seconds, all nodes stay within the range of the user, and therefore all the packets sent by the user are received by the nodes. The average success ratio is 0.73. This means that for the considered setting, on average 73% of the packets generated by the user are successfully received by all nodes in the network.

Figure 3 shows the total number of packets received with respect to three different types of communication. The green curve shows the total number of packets received considering user-to-swarm communication only. The blue curve shows the total number of packets received considering the combination of user-to-swarm and intraswarm communication. The red curve shows the total number of packets received considering the combination of user-to-swarm, intraswarm, and interswarm communication. It is evident that until 150 simulation seconds, the total number of packets received for all the three cases remains the same. The main reason behind this behavior is that during the start of the simulation, all of the swarms stay in range of the user until this time. Therefore, all the nodes in the network receive all the packets sent by the user directly. Therefore, the difference between the number of packets received by user-to-swarm communication and intraswarm communication during this period is not very significant; however, interswarm communication plays a vital role in the total number of packets received.

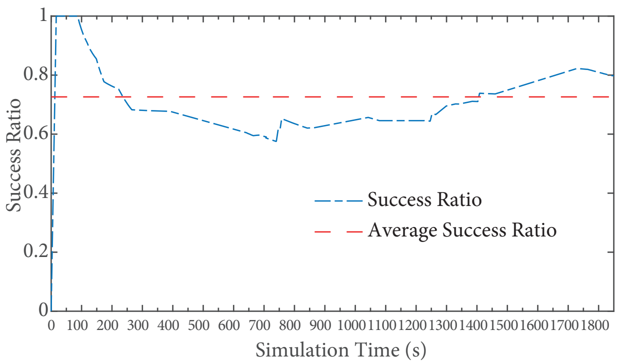

Figure 2. Average success ratio.

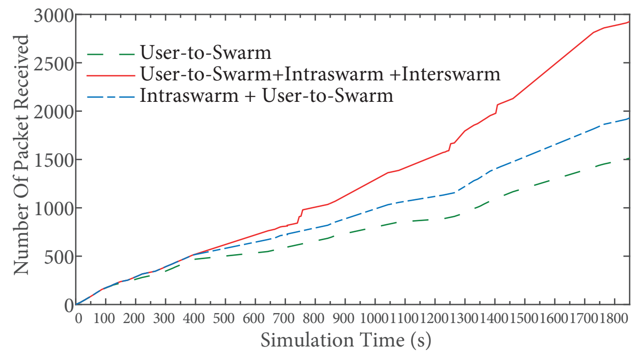

Figure 3. Packets received with respect to different types of communications.

Figure 4 shows the percentage of packets received successfully through different types of communications. This figure shows the significance of different types of communications in the total number of packets received successfully. It is evident from the figure that interswarm communication plays the most significant role, i.e. 46%. This is because when a node belonging to a swarm comes into the communication range of a node belonging to another swarm, then all the missing packets for each swarm are replicated. The overall impact of interswarm communication is significant compared to the other two types of communications. One important aspect that needs to be explored is the effect of expiry time on the number of packets received successfully. Expiry time is the amount of time after packet generation time after which a packet is discarded from the buffers of the nodes. As a result, a packet after its expiry time is not replicated anymore.

Figure 5 shows the effect of expiry time on the total number of packets received. It is important to investigate this aspect because in some cases the propagated information has temporal constraints. During our simulations, expiry time is set to three different values. Expiry time equal to infinity means that the packets in the buffer never expire and therefore they are not deleted at any time. Expiry time equal to 200 and 500 means that the packets in the buffer are deleted after 200 and 500 simulation seconds, respectively. It is observed that by decreasing the expiry time, the total number of received packets also decreases. The major reason behind this is that after the maximum expiry time value is reached, a packet is deleted from the buffer and that packet will no longer be available and will not be replicated in the future. This causes a decrease in the total number of packets received if expiry time equals 500 and 200 simulation seconds.

Figure 6 explains the trend of decrease in the total number of packets received as the expiry time values are reduced. It is evident that by decreasing the expiry time, the total number of received packets also decreases. For instance, if we set the expiry time to 500 simulation seconds, then about 31% of the packets are not delivered successfully. These results are obvious because as we decrease the expiry time of a packet then the chances of that packet being replicated decreases, resulting in a decrease in the probability of receiving that packet. Our results in this regard can help researchers understand the potential impact of expiry time on the overall received packets, particularly for the cases where the information that needs to be propagated is time-sensitive.

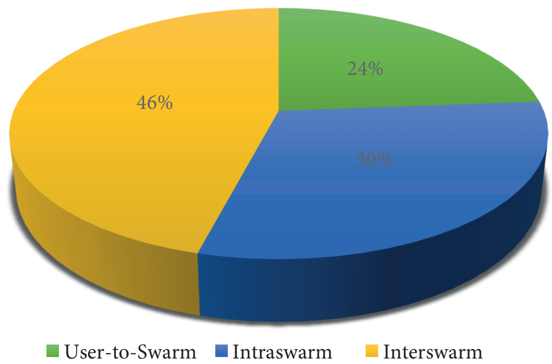

Figure 4. Packets received through different types of communications.

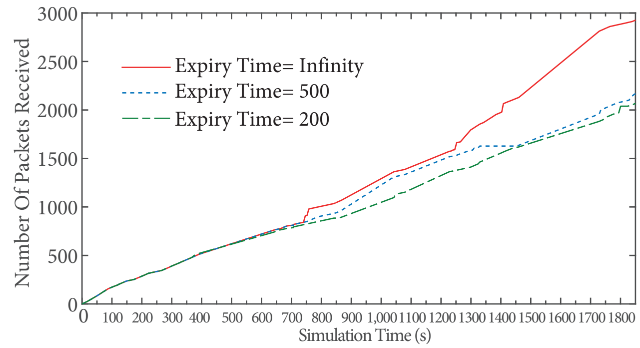

Figure 5. Role of expiry time on total number of packets received.

Figure 7 shows the coverage area with respect to simulation time. The simulation is stopped once 90% of the area gets covered and it takes 1800 simulation seconds on average to complete 90% coverage of the simulation area.

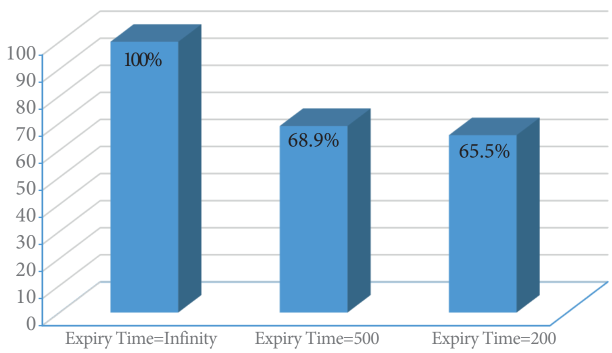

Figure 6. Impact of expiry time on total number of received packets.

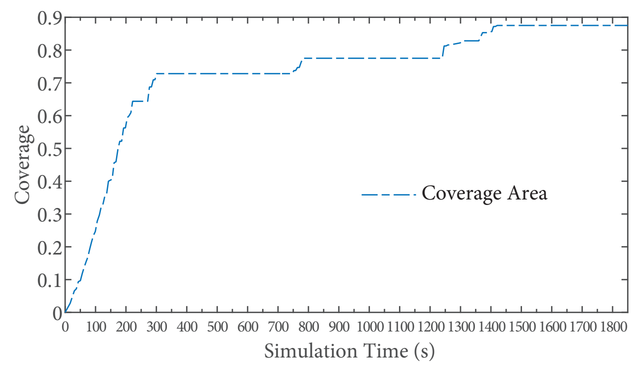

Figure 7. Area covered by swarms with respect to simulation time.

Figure 8 shows the average delay with respect to simulation time. This delay is calculated for interswarm communication only. This is because the delay for user-to-swarm and intraswarm is much smaller as compared to interswarm communication. It can be seen that values of delay start coming after a certain simulation time because after a specific time interswarm communication takes place. It is observed that the average delay stabilizes as the simulation progresses. The average delay during our simulations is 285 s.

For any performance evaluation, it is important to understand the asymptotic behavior of different simulation parameters on the considered performance metrics. For instance, increasing the number of nodes in each swarm or increasing the number of swarms within the simulation area leads to improvement in performance metrics such as number of packets successfully received and success ratio. The major reason behind this is that increase in node density within a given simulation area improves the chances of a node to get the packet successfully because there will be more nodes available to propagate packets towards a given node. Similarly, increasing the communication range (for both Wi-Fi and Bluetooth) improves the success ratio and number of packets successfully received and vice versa. The major reason behind this is that increase in communication range improves the chances of propagating a packet to a longer distance, resulting in increasing the probability for other nodes to receive that packet.

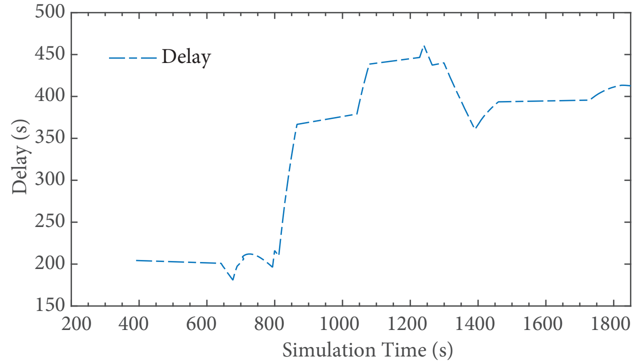

Figure 8. Average packet delay with respect to simulation time.

For this work, relatively simple settings were assumed for performance evaluation. In terms of the mobility model, it is assumed that there are no obstacles in the area. In terms of communication, particularly for Wi-Fi, a relatively simple communication model is used. Considering a more realistic mobility model and a communication model is the future work in continuation of the current research.

5. Conclusion and future work

In this paper, we evaluated the performance by considering multiple swarms in the presence of a realistic communication model with respect to multiple performance metrics like average success ratio, total number of packets received successfully, and the average delay experienced by packets. Three different types of communications were considered, i.e. user-to-swarm, intraswarm, and interswarm. The impact of each of these types of communication was investigated on the overall received packets. Unlike the existing works, it is assumed that not all the nodes in the network always stay within range of the user. Therefore, there is an intermittent connectivity among nodes and the user and, as a result, the packets generated by the user experience variable delays while reaching all the nodes in the network.

According to the simulation results an average success ratio of 73% is achieved and interswarm communication plays a major role by contributing 46% of the total success ratio. The main reason behind this is that when a node belonging to a swarm comes into the communication range of a node of another swarm then all the missing packets for each swarm are replicated. The overall impact of interswarm communication is significant as compared to the other two types of communication. Expiry time also plays a crucial role for the number of packets successfully transferred. Reducing the expiry time from infinity to 500 simulation seconds decreases the number of packets successfully received by 31%. Our results in this regard can help the user to understand the potential impact of expiry time on the overall received packets, particularly for the cases where the information that needs to be propagated is time-sensitive. In terms of average packet delay, the average delay experienced during user-to-swarm and intraswarm communication is negligible as compared to interswarm communication. The average delay experienced by packets during interswarm communication is 285 s, which is reasonable considering the node density and the size of the simulation area.

This paper will provide useful insights for researchers doing research considering multiple swarms. We have highlighted some of the major shortcomings of the existing research and also specified some of the things that should be taken into account while considering multiple swarms.

For future work, performance evaluation can be done using more realistic communication and mobility models. We have not considered obstacles in the simulation area. Therefore, future work can be done considering the obstacles in the area.

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