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A DTN-based Spatio-temporal Routing using Location Prediction Model in Underground Mines

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ABSTRACT

Situational awareness during any disaster depends on effective communication and location tracking. In the case of underground mines, where the communication methods are mostly central, the whole communication channel would be rendered unusable during a disaster. To this end, we propose the use of Delay Tolerant Networks (DTN) to allow the miners to function in a distributed manner and help in locating the injured miners and routing distress messages. Due to the unavailability of GPS signals, the pillar numbers are used to identify the locations of the miners. For spatio-temporal routing of messages, we formulate a new scheme using Contact Graph Routing (CGR) and GAE-LSTM. CGR forms routes based on the future contact (meeting times) of DTN devices, assumed to be known, which might not be the case in underground mines. Thus, we use GAE-LSTM, a graph-based deep learning model, which predicts the location of miners with time, based on the previous movement information, i.e. speed, time, angle, and location (in terms of pillar numbers) of the DTN nodes. The DTN nodes then search's for other DTN nodes which will be at the same locations at same times. Using this information, a contact plan is formed which is used by the CGR for forming a route to send the messages.

CCS CONCEPTS

• **Spatio-temporal Routing, DTN, Underground mine**;

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1 INTRODUCTION

Communication systems in the underground mine need to have a distributed architecture unlike the leaky feeder systems [2] so that in the event of a disaster, unharmed devices can still communicate. On this front, a Delay Tolerant Network (DTN) can be used to communicate and exchange messages among miners holding small tablets or similar devices. The store-carry-forward paradigm of DTNs allow nodes to create spatio-temporal paths using the contact opportunities in order to deliver messages at different locations over time. DTN nodes opportunistically communicate wirelessly (using radios/bluetooth/Google's Nearby technology) and share the information (speed, angle, time, location) of their movement. Since GPS signals are not available in underground mines, locations of miners are exchanged in terms of pillar numbers. In our architecture (Fig. 1), we assume that each pillar has a sensor attached to it that would give any DTN node around/near it the information on its current location (pillar number). Miners can be assisted faster by locating their carried devices in case of a disaster by predicting their locations using GAE-LSTM model [10]. GAE-LSTM uses Graph Autoencoder (GAE) and Long Short-Term Memory (LSTM) to formulate a model that would allow the DTN nodes to predict the locations with times of different DTN nodes in terms of pillars which helps in spatio-temporal routing of messages as nodes do not have a pre-computed routing table.

Contact Graph Routing (CGR) [7] has been shown to work in cases where the routing table for the nodes are not scheduled ahead of time. It works on the contacts of the nodes rather than the routing tables. CGR assumes that the contacts are known, i.e. the contact plans between the nodes are pre-determined. Since the DTN nodes do not have the routing table available beforehand, the information on the future contact plans is not present in the case of underground mines. The unavailability of future contact plans poses a major challenge while using CGR for DTN. We propose to extend the working of CGR by using GAE-LSTM to predict the contact plans (opposed to link prediction used in CGR) for the neighbouring DTN nodes based on probabilities of their future locations with times which can be used for routing messages.

For example, if the GAE-LSTM model predicts that Node A and Node B are going to be near pillar 10 at 1pm, we assume that they will be in contact. A collection of such contacts are used to formulate the contact graphs. Using this contact graph, a route from the current node to the destination is found using the legacy Dijkstra's method (finding the shortest path). When the DTN node searches for the routes possible, there might be multiple candidate routes present. If such is the case, the DTN node can take the decision to route multiple copies of the same message based on time to live (TTL) of message, priority of the message and other such features about the message.

To have finer-granularity in the prediction of location (pillars) of the DTN nodes for making better routing decisions, we divide the underground mine into regions and attach specific probabilities with each DTN node for being inside or outside a region. Using

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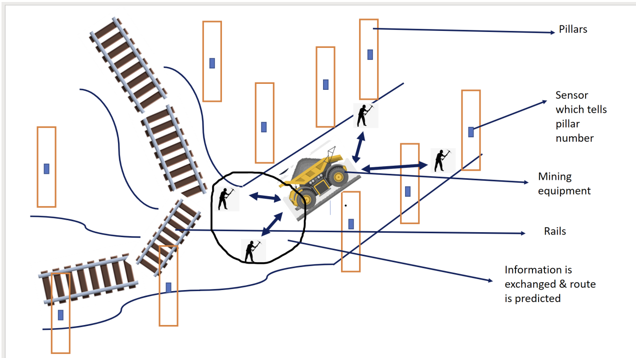

Figure 1: DTN Architecture inside the underground mine

these additional probabilities, the CGR algorithm can take a more informed routing decision when any two DTN nodes connect. Our work is novel in the following ways:

- Develop a new spatio-temporal routing scheme that would allow the DTN nodes to exploit the location prediction capability to predict the best node for multi-relay routing of messages in underground mines. The spatio-temporal routing scheme also extends the working of the legacy CGR by using additional inside and outside region probabilities of DTN nodes for better routing decisions.
- Propose the use of GAE-LSTM to enhance the working of CGR to predict the contacts with probabilities at specific locations with time.
- Develop an algorithm to allow multiple DTN nodes to use the same or similar models which would allow them to route messages as needed to minimizing the latency, increase delivery ratio and reduce energy used.

2 RELATED WORKS

DTN routing methods such as Epidemic Routing [18], Spray & Wait [7], Prophet [11], MaxProp [3] are the most widely known non-predictive routing techniques. Prophet protocol maintains a transitive delivery of prediction vector for the encountered nodes and then employs this knowledge for relay selection between nodes. MaxProp computes maximum delivery probability based on contact frequency and messages stored. Social-aware routing [[12], [17] shows how the similar interests of the DTN nodes can be used to take an informed decision to route messages. [16] shows that the mobility models, namely Random Direction Mobility Model and Time Variant Community Mobility Model perform poorly and miss out the routing performance metrics (reachability and delay). They show that both of the mobility methods work well in case of spatio-temporal and encounter statistics but lack the routing evaluation metrics. The reason for this is due to the fact that the routing and mobility schemes are based on only specific scenarios and cannot be applied to other aspects. These methods mostly are based on the past encounter experience of nodes or social similarities/interests, but they do not take into account the previous connection information. They do not have definite connection locations; at what time and where, to send messages to neighboring nodes. Many researchers have used machine learning models to choose what would the next nodes to route a particular information. Machine Learning (ML) algorithms such as Decision Trees [6] and XGBoost [4] are used for designing routing schemes. These methods are trained on the connection traces (times at which DTN nodes met previously) of different DTN nodes, which are used to predict the connection of any two DTN nodes. These methods although work well, constantly predict the connections between the nodes but not the locations where the DTN nodes would be at specific times. For example, let us assume that there is a DTN node (Node A) which, according to the ML model, is predicted to meet another node (Node B). But due to congestion, Node A could not meet the destined Node B. Node A would have to drop the message as he would not know whom to send this message next. This inability to route messages due to not knowing the locations of the DTN nodes creates an interesting problem.

[4] uses a Decision Tree to predict whether the message should be routed to the next DTN node or not. In [9], the authors use the ML classifier, namely a Random Forest to predict which of the nodes would be meeting the destination node and predicting based on the information sent by neighboring nodes on the exchange of information on the source, destination and time index.

Contact Graph routing (CGR) is another routing scheme widely adopted in the case of interplanetary routing. Contact Graph Routing can be defined as a mechanism of routing in time-varying graphs. It can be defined as a directed acyclic graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ at time t_c where $\mathcal{V}$ are the vertices which represent the interaction or the exchange of information amongst the nodes and $\mathcal{E}$ is defined as the edges which retain the message or information in between the interactions. Multiple works [[1], [7]] have shown the different ways in which CGR can be a better routing method than others and can also be extended to routing in DTNs under uncertain contact plans. [5] shows in their work how CGR can be used for finding the shortest route in time varying graphs. They first find the set of edges or contacts that take place before the time to live (TTL) of the message expires. Using the edges formed and contacts found, they formulate a routing path. They assume that the edges or contacts are known beforehand, which is not the case in underground mines. Although they add the TTL component, as they focus on space routing, they miss the prediction of location as an aspect which we have addressed in our work. We also take into account the region probabilities to give find grained knowledge of the motion of the DTN nodes which adds accuracy to the GAE-LSTM model. [14] works on Temporal Random Walks (TRW) where the authors show and prove the drop probability of a message given the time varying movements of the nodes. They also explore the idea of passing of token in case of contacts. They however do not predict the location and then use that information for prediction. They also do not talk about probabilities of how and where the token/messages should be sent for optimal routing. In both of these applications, the authors mention how the information is relayed by forming a contact graph for which the contacts are known a-priori. In [7], the authors show how routing under uncertain contact plans can also be used with CGR.

Our work predicts the approximate location of a DTN node with respect to pillars at different times in future, and then uses this

predicted location to decide if the node should route this message to the current neighboring node.

3 PROBLEM STATEMENT

Consider a given underground mine where no GPS signals are available. Given a message $\mathcal{M}$ at time t_i with DTN node X at a particular location inside a mine. Consider a set of neighbouring DTN nodes $N = A_1, A_2 \cdots A_n$ of the node $\mathcal{X}$. The objective is to calculate the best node/set of nodes BN where $BN \subset X \cup N$ that will route the message $\mathcal{M}$ to the destination node say D at another location at time t_j such that it minimizes the delivery time (DT).

4 THE GAE-LSTM CGR MODEL

As mentioned earlier Contact graph routing (CGR) is a dynamic routing algorithm that computes routes through a directed acyclic time-varying graph of scheduled communication contacts in a DTN network [1]. The assumption in CGR is that the link availability (meeting times) is known a-priori, which might not be the case with a DTN in underground mines. Due to the movement of different types of DTN devices (e.g., vehicles, trollies, miners) at different times it is impossible to predict the contact and wait for their arrival. In addition to this, during a disaster, the whole setting falls into disarray and normal working conditions are hampered. Hence, we use GAE-LSTM model to predict the locations of the miners (in terms of proximity to pillar numbers) at future timestamps. In addition to this, we extend the working of CGR by also adding for each DTN node probabilities for being inside and outside a region. Inside a region probability is the probability any given DTN node meeting other DTN nodes in the same regions whereas the outside probability is the probability based on how frequently a given DTN nodes travels to a different regions. Both of them are additional aspects of the underground mine that are used by our routing method when taking the decision of routing a message. The GAE-LSTM CGR Model is divided into the following categories: contact, model prediction, contact plan, contact graph routing

4.1 Contact

The contact is denoted as the interaction that happens between any two DTN nodes. We assume that when any two nodes are near any pillar, or are nearby same pillars, they can communicate with each other (as mentioned earlier, using the radio/bluetooth/Google's Nearby equipped devices). During this communication, the DTN nodes exchange information such as speed, time, angle and location (pillars) on their movement mutually.

4.2 Model Prediction

Once the movement information has been received by the DTN nodes, it is passed to the GAE-LSTM model. The model then predicts a new set of future locations of neighbouring DTN nodes with times. There might be multiple locations of a particular DTN node that are predicted for a specific time. The DTN node selects the location (pillar) which has highest probability of being at a particular time.

The intuition behind GAE-LSTM model is to predict the locations (pillars) of the miners. These locations can then be used to exactly known where the miner is headed, leading to better contact plans. To explain in brief, the GAE-LSTM model consists of the Graph Autoencoder (GAE) which captures the modelling of the pillars in the underground mine. The Long-Short Term memory (LSTM) is used to capture the movement representation of miners around the locations (pillars).

4.3 Inside and outside a region probability

In this work, in addition to using GAE-LSTM for enhancing the working of CGR, we also use probabilities for a DTN node being in inside and outside a region. To obtain fine-grained granularity on the prediction of the locations, we further divide the whole mine into smaller regions as a logical division of the mine into a set of pillars. We mention these regions as $r \in \mathcal{R}$ where r pertains to a subset of locations (pillars) and $\mathcal{R}$ is the set of all locations (pillars).

The inside probability of a DTN node A_i with respect to A_j in the region r is the number of times a connection was made between DTN node A_i and DTN node A_j divided by the total number of all contacts made with A_i by other DTN nodes in the same region r. The inside probability is formally calculated using equation 1:

$$Pr_{in}(A_i, A_j) = \frac{\sum A_i, A_j}{\sum_{k=1}^{k=DTNnodesinregion} A_i, A_k} \tag{1}$$

Similarly, the outside probability of a DTN node A_i with respect to region r can be calculated as the number of times DTN node A_i visited region r divided by the total number of times DTN node A_i visited all the regions except its own. It is formally stated in equation 2 below:

$$Pr_{out}(A_i, r_i) = \frac{\sum A_i, r_i}{\sum_{k=1}^{k=numberofregions} A_i, r_k} \tag{2}$$

where A_i is the current DTN node, r_i is any given region.

We add this aspect of movement of the DTN nodes to transmit the message in the least possible time to improve the delivery time. By combining the contact probability from GAE-LSTM with the outside and inside region probabilities, we can get a combined delivery probability $Pr_{delivery}$ to decide the next best neighbour to send the message.

$$Pr_{delivery} = Pr(RP) * Pr(CP) \tag{3}$$

where $Pr(RP)$ is the region probability. The decision on taking into account the outside or inside a region probability depends on the DTN nodes' current location and the neighbouring nodes regions and locations. $Pr(CP)$ is the contact probability of the two DTN nodes as predicted by GAE-LSTM.

4.4 Contact Plan

Once the future locations and times of all the nodes are selected, then this node can make a decision on whether the information should be sent to which of the available nodes. There might be other DTN nodes that are not in contact with the current DTN node but were in contact earlier. Previous predicted information on the movement of other non-connected nodes is also used by the current DTN node to form the routing plan. Using the predicted location and times information available, the node comes up with a new contact graph. This contact graph is a bit different than used conventionally. The contact plan formed does not have the start and

the end time of contact rather they have a certain time of contact, for example, this graph would not mention the start of the contact, 3 pm, and the end of the contact, 3:05 pm. This graph only mentions that the two nodes will meet at 3pm. The reason for this is that we do not have a perfect sense of the duration of the connection due to the dynamic nature of the movement of the nodes. The model allows us to know when and where the nodes will be meeting in the future. A sample contact plan can be seen in Table 1 with respect to Fig 3. Using the contact plans generated, we use the same contact graph routing method as before.

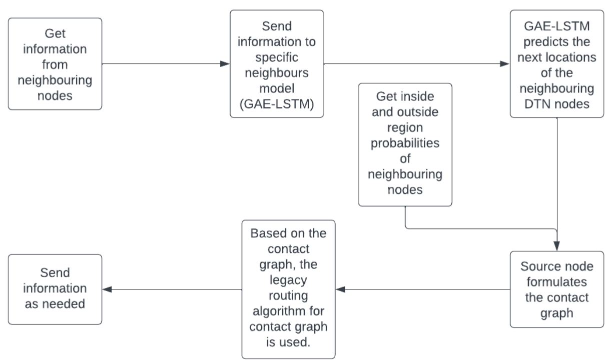

Figure 2: Flow chart of the GAE-LSTM based CGR

4.5 Contact Graph Routing

After the contact plans are generated, the route for the transmission of this message is calculated. [15] in their work mention about the calculation of partial route i.e. only nodes that are going to be connected in the same time slot. But, we differ in our route definition here. Due to the ever-changing variation in the contact of the DTN nodes, we predict the locations (pillars) for the foreseeable future for different times, i.e. more than one time slot. In addition to the information on the contact plans, when routing, the DTN node also looks at the region of the destination node. If the region of the destination node is the same as that of the current node, then it means that the inside region probability will be used when routing the message whereas if the region of the DTN node is different than that of the current DTN node then the outside region probability is used to take the routing decision.

Example Let us say that there is a message *m* which was generated by the source DTN node *S*, and has to be routed to the destination DTN node *D* within time period *T*. Now, let us assume that the node *S*, meets three DTN nodes (A, B, C) at 10am. As none of them is the destination DTN node *D*, they would be the intermediate nodes. Here, we assume that the node *S* does have some stored information on the other nodes that it is not meeting at 10am. Each of the nodes exchange mutually their own movement information (speeds, angles, time, and locations (pillars)). The movement information is passed to the GAE-LSTM model at *S*. The GAE-LSTM model predicts the locations with time of the neighboring nodes (A, B, C). In addition, the GAE-LSTM model also gives the probability of the predicted nodes being at specific locations with time. As mentioned in Fig. 1, the probability of a contact taking place between A and D is 0.8 at 2pm. Similarly, the probability of a contact taking place between E and D is 0.75 at 4pm. And, node C might not meet D at all. An important point to be noted here is that the prediction probability accuracy of the contacts decreases as the prediction horizon increases, i.e. the prediction accuracy would be higher for the next 1 hr interval than the prediction accuracy for the next 6 hour interval. The reason for this is due to the fact that as we predict the locations of nodes with larger time windows, due to the dynamic nature of underground mines, the previous information becomes stale leading to lower accuracy in prediction of probabilities of locations. The model cannot take into account the real-time changes in the movement of the nodes. The contact plans made by *S* can be seen in Table 1. Note that the data rate is not predicted by the GAE-LSTM model, as that information is based on the communication bandwidth between the DTN nodes when they meet. In addition to the probability of the contact, the DTN nodes also take into account the inside and outside a region probability of other nodes when in contact. In the above example, assuming two regions in the underground mine, DTN node *S* would compare the outside and inside region probabilities of all the neighbouring nodes (A, B, C). Let us assume that the destination node D is outside the current region of *S*. As can be seen from the figure 3, node *S* has the information that nodes A and B have higher outside region probability than node C and hence it would send the message to both nodes A and B but not to node C. DTN node *S* compares the outside region probabilities of all the neighbouring nodes A, B, C. If node *S* would have been in the same region as that of the destination node D, then we only would have compared the inside region probabilities of the nodes.

Table 1: Contact Plan

Node start	Node end	Time	Data Rate
A	D	2pm	10mbps
B	D	1 pm	10mbps
A	E	1pm	10mbps
B	E	2pm	1mbps
E	D	4 pm	2mbps

Using this information, a contact routing graph is made. The contact routing graph is a directed acyclic graph structure where the vertices represent the interaction or the exchange of information (speed, angle, time, locations(pillars)) amongst the DTN nodes and the edges show which DTN nodes retaining the message in between the interactions.

The process of getting information from neighbouring nodes, followed by sending this information to the GAE-LSTM model and formulating contact plans based on the predicted locations (pillars), all happens at each DTN node that gets the message. Once the message is routed to the neighbouring nodes, the intermediate DTN node becomes the new source and the process of getting information (speed, angle, time, location) to predict locations (pillars) is repeated. For example, once the source DTN node *S* decides to send the message to, DTN node A, it becomes the new source node and repeats the process of calculating which of the neighboring DTN nodes to send this message.

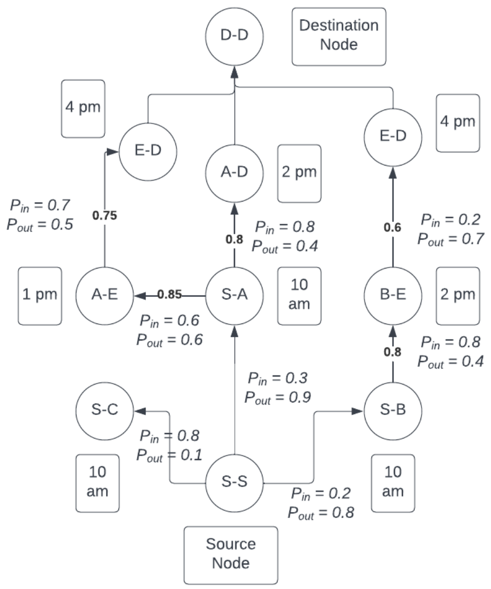

Figure 3: Flow chart of nodes movement. The probability value on the edge (in bold) show the probability of the predicted probability of meeting by GAE-LSTM. The P_{in} & P_{out} are the inside and outside a region probabilities

It should be noted that the times for which location prediction by GAE-LSTM takes place is limited till which the message has to be received by the destination node. Let us assume that in the previous example, the message has to be received by the destination D till 2 pm and *S* predicts that nodes A, B, C can route the message to D but not till 4 pm, then it does not make sense to send the information to either of the nodes (A,B,C). In such a case, the DTN node *S*, should wait for other nodes that it might meet for sending information.

Another important aspect to be considered when deciding the route is the probability of contact. As can be seen in Fig. 2, the edges mention the probability the contact between any two nodes. Based on the neighbouring nodes, the current node, in this case *S*, can decide whether it wants to send this information or not. The threshold to decide which node to send information to can be set dynamically.

We show the contact graph in Fig. 3. The nodes in the graph pertain to the interactions between the DTN nodes. The interaction times are mentioned next to the nodes. It should be noted here that as we are working with DTN, the structure of this graph will change based on new information gathered by the movement of the DTN nodes. An intermediate DTN node, based on new information, might decide to route this message to a different DTN node than what was originally planned. It can also be seen that at each edge, the prediction probability has been mentioned. This prediction probability is associated with the node (contact) the edge points to. As can be seen from the figure, the prediction accuracy decreases with time. Based on the information given to *S* at 10 am, both nodes A and E will be in contact with destination node D after certain timestamps, it will send information to both A and E. The reason for sending multiple copies of the same message is that as the nodes move, there might be a case in which node A or E do not meet due some other circumstances or congestion in certain areas. Hence, if the message was sent to only 1 node, then the message has a higher chance of failing. We will further, in our simulations, study how and what are the number of packets that should be sent to the nodes so as to achieve a high delivery ratio with low latency.

5 FORMAL GAE-LSTM CGR ROUTING ALGORITHM

Here, we provide the formal algorithm that allows the DTN nodes to route information based on the GAE-LSTM location prediction framework integrated with CGR explained in the previous section.

Algorithm 1 Spatio-temporal Routing of messages based on location prediction by GAE-LSTM when a new connection between a node $\mathbf{u}$ and nodes $\mathbf{v} = v_1, \cdots, v_k$ at time t_c has been established

Input : source, destination, ttl, priority
Output : next best router ‘ **procedure** SENDMESSAGE *(u, msg, v)*:

1: **for** $\mathbf{v}_k$ in v **do**
2: **if** *msg*.destination == $\mathbf{v}_k$ **then**
3: forward msg *m* to $\mathbf{v}_k$
4: **end if**
5: Get data $D \in (speed, angle, time, locations(pillars))$ from $\mathbf{v}_k$
6: Send data to the GAE-LSTM model
7: Get predicted location information for $\mathbf{v}_k$ from the model
8: Calculate the route based on inside and outside region probabilities
9: Create a partial route for message transmission
10: Route message to the next node on contact
11: **end for**

Here we explain in detail working of the routing protocol mentioned in algorithm 1. The working of the algorithm explained here is from the perspective of a single DTN node. This algorithm will run the same way at all the DTN nodes. Once the DTN nodes come in **contact**, the algorithm first checks (Lines 2-4) if any of the neighboring nodes are the destination nodes. If that is the case, then the message is routed. If not, then we know that the neighbouring nodes for now are all intermediate nodes. The DTN node (node **v**) first gets all the information of their movement, i.e., the speed, angle, time, location (pillars) of their movement (Line 5). The movement information collected can be past information that might not be useful now but it is beneficial to collect such information as it will help in learning the movement pattern of the DTN node. Next, this information is sent to the ML model (GAE-LSTM) (Line 6). The **GAE-LSTM model predicts** the location of the neighbouring nodes at different time intervals (Line 7). The GAE-LSTM model also gives the percentage of possibility that any two nodes will connect in future. This probability is used when deciding which route to take for delivering the message. Using this location information, a **contact plan** is formulated as explained earlier (Line 8). This contact plan has the information of when the contacts will happen

between the DTN nodes at different times. Using this information, the contact graph can be formed as shown in Fig 3. This contact graph entails the different contacts between DTN nodes as the nodes of the graphs and the edges form the connections between these. The edges can also be thought of as information storage between any two consecutive contacts. Once this **contact graph** is formed, the shortest path is found using Dijkstra's algorithm as used in the legacy CGR method to route the message (Line 9).

6 FUTURE DIRECTIONS

We will simulate the proposed spatio-temporal routing algorithm using ONE simulator to evaluate the performance in terms of message throughput, latency, energy usage, etc. We will use the underground mine architecture and different nodes predicted positions and times to store and forward data and how long. For example, some nodes may move only for a small period but may be at some strategic locations so they can store data for longer times. We will also experiment to determine the average number of copies to be forwarded, and how long they are stored based on the time remaining for delivering messages. It is expected that it will lead to a better delivery time, increase throughput and also better energy usage with reduced hops. We will compare the model with some other competitive routing schemes [13] and the CGR schemes [5, 8, 14]. [16] shows in their work that the mobility scenarios they tested did not work well for some use cases and also lack the performance metrics when applied to real-life scenarios. We would test our routing scheme on real-life scenarios to show that our routing scheme is scenario agnostic. We will test this work also using the Federated Learning (FL) concept where the data would not be sent to the DTN node, rather only the gradients of the model will be sent to the neighbouring DTN's GAE-LSTM model. This will further reduce latency, communication bandwidth and energy usage as well. We will compare the energy usage in training the model vs. energy used in the communication while sending data to other nodes.

7 CONCLUSION

Situational awareness in underground mines is important for rescue operations during times of a disaster. In underground mines, the communication systems are mostly centralized which are rendered unusable in case of a disaster. Here, we propose a new method for spatio-temporal routing of messages integrated with location prediction of miners using the wireless communication based on DTN in the underground mines. A DTN allows the miners to operate and communicate opportunistically, which can be helpful in case the need arises to know the location of miners at certain times. The locations of miners are predicted with respect to pillars, in the absence of GPS signals inside the underground mine. We extend the working of the legacy contact graph routing (CGR) method by using our custom GAE-LSTM model for link prediction based on the location prediction for the intermediate nodes. To increase the delivery probability, we divide the underground mine into a set of regions where a region is a geographic categorization of a set of pillars. Using these regions, and the DTN nodes' frequency of meeting other DTN nodes inside the region and outside a given region allow DTN nodes to take better decisions of routing messages to the correct DTN node. Our proposed routing scheme uses GAE-LSTM to predict contacts, removing the need to know the contact plans beforehand as is the case in the legacy CGR method. In the case of a DTN, due to the movement of miners, it is an impossible task to know the interactions possible beforehand as used in CGR. We show that the GAE-LSTM method used for the prediction of locations with respect to the time of DTN nodes can be linked to the prediction of contacts of miners. Our model is expected to perform well compared to competitive schemes as stated in the future work.

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