# Bubble Routing: Intelligent Terahertz (THz) Data Forwarding Over Flying Ad-Hoc Network (FANET) with High Mission/Mobility Dynamics

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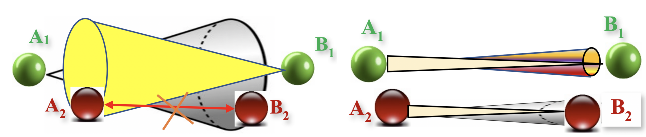
***Abstract*—The Terahertz (THz) links transmit signals with extremely high-frequency carrier (01-10THz) to achieve a data rate of over 100 Gbps. THz nodes need to use pencil-like narrow beams to carefully align with each other to achieve low-fading-loss transmission. This research aims to build a THz network routing scheme in the flying ad-hoc networks (FANET). Particularly, we target the mission-oriented FANET with high node mobility (>100m/s). A mission-driven FANET could have different task assignments for each region of the network, and the nodes belonging to the same mission region form a 'bubble' due to their movement consistency. Those bubbles can float around, burst up, get merged, or shrink down. We then propose the concept of *bubble routing* with three novel features as follows: (1)*Intra-/inter-bubble THz link management:* From a source bubble to a destination bubble, the inter-bubble and intra-bubble THz links are established to form a complete path. The path has THz *bundle* for higher throughput by establishing multiple links between neighboring bubbles (inter-bubble). Inside each bubble (intra-bubble), the representative of the bubble (ROB) coordinates the Tx (transmission) / Rx(reception) activities between all active nodes. (2)*Intelligent THz bubble state prediction and reactions:* To achieve mobility-adaptive THz high-rate transmissions, we propose to use "long short-term memory (LSTM) + graph convolutional neural network (GCN) + generative adversarial network (GAN)" to accurately predict each bubble's node/link changes. The predicted bubble topology further severs as the inputs for path maintenance purpose. (3)*Altitude- and congestion-aware THz path establishment.* Because THz channel fading is closely related to the altitudes of flying nodes, we have different link setups for the bubbles located in different altitude levels. Meanwhile, because the huge THz data amount can easily overwhelm the queues, we closely monitor the distribution of traffic loads by using the concept of *traffic heat map* (THM). Bubble routing can avoid heavy-traffic bubbles (i.e., congestion-aware). Comprehensive simulations have been conducted to validate the adaptivity and robustness of the bubble routing in dynamic FANETs.***

***Index Terms*—Terahertz (THz) communications, Routing protocol, Flying ad-hoc network (FANETs), Deep Learning**

## I. INTRODUCTION

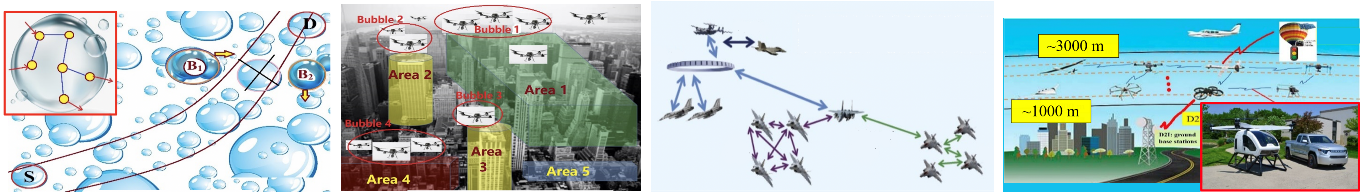
THz's spectrum (0.1 10THz) has drawn many attentions because of its huge bandwidth and its potential for ultra-high data rate (>100 Gbps) [1]. However, it has very short wavelength and high attenuation in free space, and requires a pencil-like narrow beam to concentrate the transmission power in a specific direction. In low-frequency networks (such as WiFi), a pair of nodes (for example, $A_1$, $B_1$ in Fig. 1(1) with general directional antennas (with large beamwidth), may not allow nearby nodes (say, $A_2$, $B_2$) to establish a link due to the mutual RF interference. However, THz's narrow beams make the link ($A_1$-$B_1$ act like a **pseudo-wire** (Fig. 1(2)), which means that even very close neighboring nodes can establish communicate links. Therefore, THz links in a neighborhood have very low chance to cause channel access conflicts. This fact makes it possible to *establish multiple THz links in a small neighborhood.*




(a) Conventional directional links (b) THz pencil-like beams
Fig. 1

However, the above THz advantages come with some costs: (1) *Requirement of tight node coordination:* The sender and receiver must have highly accurate antenna alignment. Even a little beam mis-orientation can cause significant packet loss [2]. (2) *Suffer from scattering attenuation:* The scattering effect of THz communications in the near-earth atmosphere cannot be ignored [3]. Meteorological factors, such as rains and clouds, have significant effects on scattering attenuation of THz waves. Thus, it is difficult to use THz waves in the low-altitude (i.e., near-atmosphere) environment. However, molecular absorption and scattering attenuation may not be the major issues in high-altitude space (vertically-up from 10 km to 12 km [4]), where water drops are much lesser. (3) *Distance-selective nature:* THz channel is sensitive to link distance changes. In fact, different THz spectrum windows (i.e., sub-bands) are preferred for different node-to-node distances [5].

The dynamic network condition of the flying ad-hoc network (FANET) is another challenge for the THz network protocol design: (1) *High mobility:* An aircraft can move at >100 m/s. Due to the distance-selective nature of THz channels, frequent THz channel handoff may be required. (2) *Node posture change:* Even with a small change of node posture (such as tilting, shaking, elevation, etc.), the antennas can lose accurate alignment and thus cause THz link failure. (3) *Mission diversity:* FANETs often have certain task/mission requirements. For example, the nodes may need to monitor different city areas in environment surveillance applications. *Within each area, the nodes typically show similar mobility*




(a) Bubble routing concept (b) City surveillance (c) Military airborne network (d) Sky transportation

Fig. 2: Comparison of Three Routing Schemes.

*patterns for coordination convenience.* Note that the missions may change in battlefield or swarming applications.

In this paper, we target *intelligent THz routing protocol that can establish/maintain optimal THz links for large-scale FANETs with both mobility and mission dynamics.* We propose the concept of bubble routing (Fig. 2(a)) to handle vulnerable THz links in dynamic networks. Each bubble represents a group of nodes with similar mission/mobility modes. During route seeking process, a source bubble needs to search a chain of suitable bubbles (called *bubble chain*) to reach the destination bubble. For inter-bubble communications, multiple bridge links may be established to connect neighboring bubbles by using high-directionality antenna. For intra-bubble routing, a representative of bubble (ROB) can be selected to coordinate the bubble's internal communications.

The above bubble concept fits many FANET applications well. For example, in homeland security applications, various groups of nodes are deployed to monitor different city areas (Fig. 2(b)). In military airborne networks (Fig. 2(c)), the aircraft often form different group sizes (such as squad, platoon, company, etc.) to adapt to mission varieties. Future sky transportation (Fig. 2(d)) can greatly relieve the congested ground transportation. Each sky lane has the same speed limit and trajectory (thus each lane of vehicles can be seen as a *bubble*). In the extremity case, if there is only one node in each bubble, the routing goes back to conventional multi-hop mode. General routing schemes (e.g., AODV [6]) may be used.

Although conventional cluster concept [7] also divides nodes into subgroups, its criterion is mostly based on physical proximity, and often assumes that the entire network has similar mobility pattern. While in our bubble concept, bubbles are built based on missions assigned to different node groups. Nodes with the same mission have similar mobility pattern and thus can be classified into the same bubble. Inside the same bubble it has higher probability to build stable THz links. Moreover, our bubble concept reflects the float, burst, merge, and split behaviors among different bubbles in mission-oriented FANET applications. The ROB can send the control messages to the boundary nodes of the bubbles to establish/demolish inter-bubble bridge links. Another difference is: clustering mainly relies on the cluster heads (CHs) for inter-cluster communications (i.e., all data are communicated through CHs), while in our bubble concept, a ROB may not get involved into data transmissions as long as there exits a shorter path to reach a bridge link.

**Contributions:** The attractive features of our bubble routing scheme include 3 aspects as below:

**(1) Intra-bubble and inter-bubble THz links management:**

Since THz links are highly sensitive to antenna misalignment and link instability (caused by node mobility/mission changes), we distinguish between the relatively stable intra-bubble links (inside each bubble) and the more dynamic inter-bubble links (between bubbles) as below:

- For *intra-bubble* forwarding, a ROB can manage the input/output THz flows through predictive path selection and adjustments. Such a scheme aligns different antenna pairs with the minimum RF interference. It aims to reach the maximum intra-bubble throughput.
- For *inter-bubble* relay, some *boundary nodes* of a bubble could simultaneously establish multiple THz links with the boundary nodes of another bubble. This is based on the above-mentioned THz antenna's *pseudo-wire characteristics that allows multiple pairs in a small neighborhood to establish conflict-free links.* The ROBs of neighboring bubbles closely coordinate with each other (such as sharing bubble topology map) to manage the inter-bubble links.

As we can see, the benefits of using the bubble concept are multi-fold: It fits well many practical airborne network applications with regional mission/mobility similarity; It has inter-/intra-bubble THz link management to handle the different link stability levels inside/outside the bubbles. Moreover, it helps to overcome **1/4-duplex** issue: As shown in Fig.3 (1), it is not uncommon that a node needs to relay the packets for two (even more) paths' flows. Here node A needs to switch its directional antenna among 4 different neighbors (i.e., ¼ duplex). As we know, even for a single path, a node can only work in *half-duplex* mode (i.e., it cannot send data to its downstream node when it is receiving data from its upstream node). If there are two paths, the node has to operate in ¼-duplex mode. This can decrease the network throughput since each path obtains only ¼ of the antenna time (assuming the antenna stays the same time in each direction).

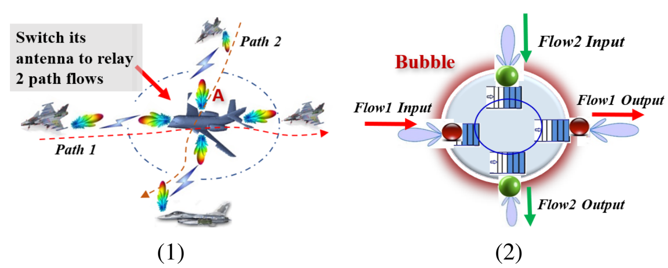



Fig. 3: (1) 1/4-duplex issue. (2) Bubble can achieve 360° multi-duplex

As seen in Fig. 3(1), our bubble concept can overcome ¼-duplex issue because we replace a single intersection node

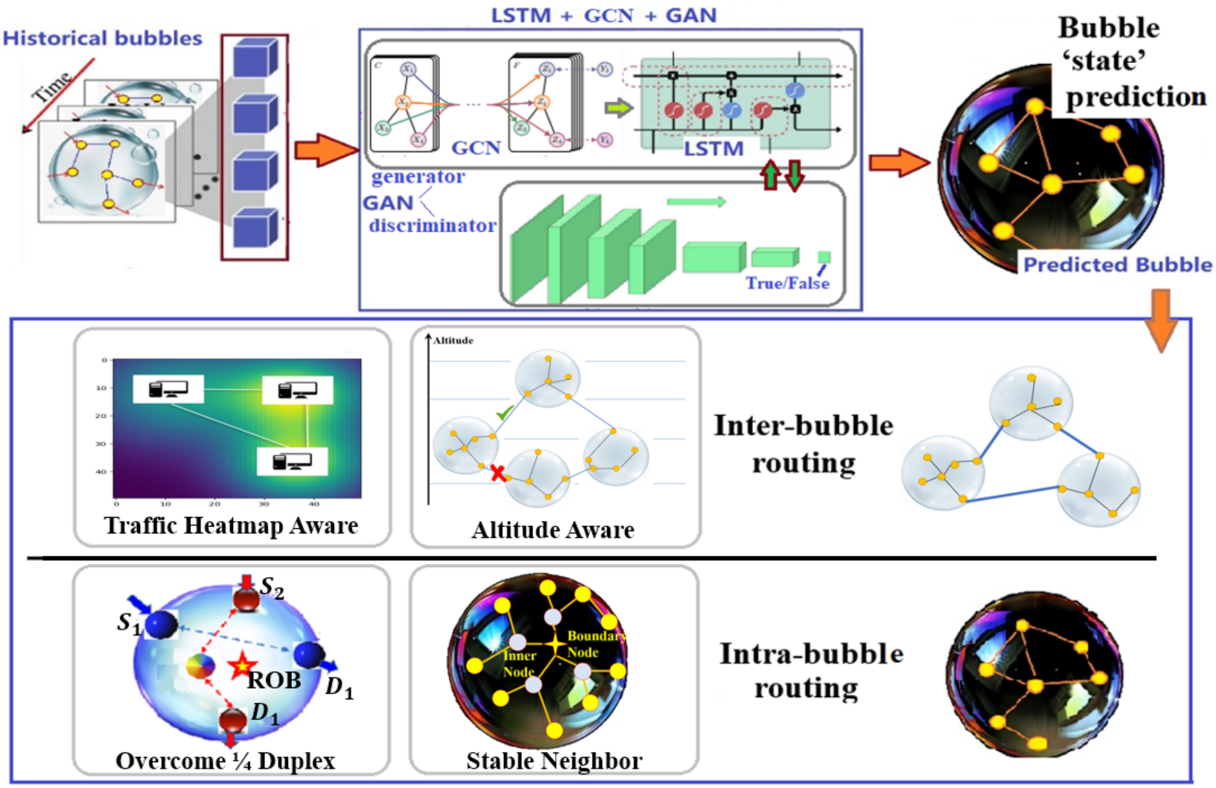



Fig. 4: Concept of Bubble Routing

with a bubble. The ROB manages intra-/inter-bubble links for different paths that pass through the same bubble. Moreover, bubble routing scheme can optimize the flow rates of different paths by using *predictive* transmission (Tx)/Reception (Rx) scheduling.

Our routing scheme also performs *bubble membership management.* A bubble can float around without membership change; it can also 'burst out', i.e., it is decomposed into smaller bubbles due to mobility pattern diversification in the same bubble; or two (or multiple) bubbles are merged into one if they get very close and have similar mobility patterns; a bubble can also grow (if a new member joins) or shrink down (if a node leaves).

**(2) Intelligent THz communication state/action determination:**

THz links require accurate alignment between the transmitter and receiver's narrow antenna beams (beamwidth<20° [8] Due to the ultra high THz data rate, it is often too late if we wait for the detection of antenna misalignment and then pause the transmissions. For example, within just 100 ms of link outage, dozens of packet batches (each batch consists of 100 packets with a size of 10k bytes each) may get lost.

Therefore, we propose proactive coordination between any two THz nodes. Particularly, the ROB keeps track of each bubble node's **state**. It uses the historical bubble snapshots (graph-represented bubble topology) to *predict* the next-time bubble parameters (node position, velocity, pitch/yaw/roll angles, link SNR, etc.). To achieve spatio-temporal continuous prediction, we first extract network topology patterns through graph convolutional network (GCN). Then, a long-/short-term memory (LSTM) module is added to the GCN to explore evolutionary trends. Meanwhile the generative adversarial network (GAN) is used to improve the bubble state prediction accuracy. The final THz route selection and adjustments are made based on the predicted bubble states.

**(3) Altitude-/congestion-aware THz path establishment:**

THz is not only *distance-selective* (i.e., different link distances prefer different THz bands), but also *altitude-selective*. Based on the THz channel characteristics for airborne networks [9], the lower altitude (<5 km) favors the THz band (0.1-0.4 THz) since other bands have large fading loss. Our inter-bubble routing scheme establishes different number of THz links for load balancing among bubbles located in different altitude levels. Bubble routing attempts to establish a bubble chain that passes through higher altitudes.

*Congestion-aware* path seeking: Due to THz's huge data transmission amount, a node's queue can be easily overwhelmed if the traffic gets stuck in any node. Our bubble routing scheme selects inter-/intra-bubble links with lower chance of congestion. Particularly, we propose to build a *traffic heat map* to indicate the congestion levels of different bubbles. Such a heat map also serves as the inputs to "LSTM+GCN+GAN" model for the prediction of congestion evolution trend.

The entire framework of our bubble routing scheme is shown in Fig. 4.

*Paper organization:* The rest of this paper is organized as follows: Section II summarizes the related studies in this area. In Section III we elaborate the protocol details of bubble routing. The simulations results and performance analysis are explained in Section IV, followed by the conclusions in Section V.

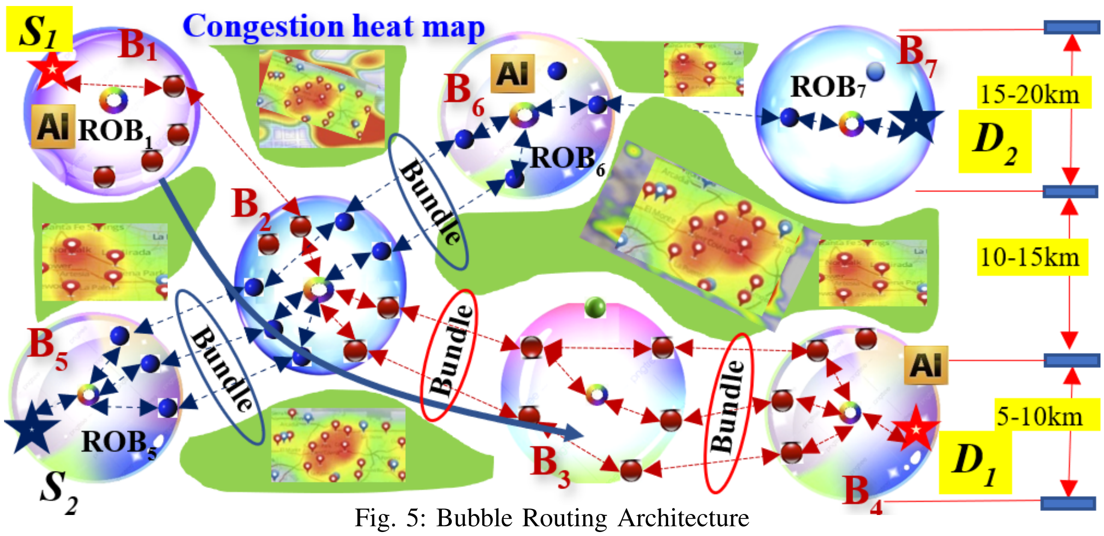



Fig. 5: Bubble Routing Architecture

## II. RELATED WORKS

### A. *Ad hoc Routing*

Ad-hoc routing has been studied for decades. Ad-hoc On-demand Distance Vector (AODV) and Optimized Link State Routing Protocol (OLSR) are the two most widely used routing protocols. Such schemes typically search for more stable links [10], or use energy-efficient flooding [11], or choose links with less congestion [12]. The routing messages are often modified to exchange network topology information. For example, OLSR HELLO message can be modified to carry such information [13]. Unfortunately, none of the conventional routing schemes have considered THz channel properties. In THz networks, it is critical for nodes to coordinate with each other well since even *1-ms* of link failure can cause the loss of hundreds of packets. THz routing protocol should consider altitude level, link capacity/stability, node mobility, and congestion situation, in order to fully explore the high data rate of each THz link. Moreover, in this paper we target mission-oriented bubble-based routing. The conventional routing schemes are not suitable to bubble topology. They also did not consider the coordination issues for the inter-/intra-bubble links.

### B. *THz Network Protocols*

THz network protocols are still on its early studying phase. In [14], Qing introduced a dual Q-learning based THz channel routing scheme. They defined reward function with respect to buffer vacancy rate, link collisions, and deflections. However, their scheme is a *reactive* protocol while our routing uses *proactive* approach through deep-learning-based prediction model to coordinate Tx/Rx transmissions.

## III. BUBBLE ROUTING

### A. *THz Channel Properities*

THz channel capacity is highly affected by geographic and atmosphere effects, which include altitude, temperature, water vapor concentration (humidity), and so on [10]. Our THz channel model is a multi-section linear approximation of the model in [9]. The channel capacity 'Cap' drive is based on the following physical model [9]:

$$Cap(z_1, z_2, d) = \Delta f * \mathbb{E} \sum_{k=1}^{K} log_2(1 + \frac{P_T^k * |h| * G}{P_n(f_k, z_1, z_2, d, \Delta f})) \tag{1}$$

Where $z_1$ and $z_2$ are the transmitter and receiver's altitudes, respectively; $d$ is the distance between them; $\Delta$f is the band gap; $\mathbb{E}$ is the expectation. In the *log(.)* function the signal-to-noise ratio is used. $h$ is the total channel coefficient; $G$ is the antenna gain; $P_n$ is the noise power. Both $P_n$ and $h$ are strongly related to the altitude level. Overall, the altitudes ($z_1$ *and* $z_2$) and distance $d$ are the key effects for THz channel properties. When the altitudes $z_1$ *and* $z_2$ go up, the THz channel capacity $C$ also increases. Also, *'Cap'* exponentially decays as $d$ increases. Due to the limited Tx power and high propagation loss, directional antennas with narrow beams should be used [14].

### B. *System Assumptions*

To fully utilize the advantages of THz links with ultra-high data rates, we only use THz directional links for **data** transmissions. In other words, the background protocol messages (typically with a size of <100 bytes) are sent on the low-frequency channel (e.g. WiFi 2.4 GHz or ku-band 15 GHz) with slower data rate. During the neighbor discovery phase, each node periodically sends the HELLO message to detect neighbors. Sidibe et al. [15] discovered that the omni-directional antenna (OA) takes lesser time to discover the neighbors than directional antenna. Thus, we use OAs to exchange control messages and highly-directional THz antennas for data packet delivery.

Medium Access Control (MAC) protocol for THz links should 1) accurately coordinate the transmitter's and receiver's antenna orientations in a short time window; 2) properly allocate/assign channels to users to improve the channel utilization and avoid buffer overflow. In this work, we assume that our previously invented MAC scheme [16] is adopted below this proposed bubble routing scheme.

### *C. Routing Architecture and Principles*

Before we describe the details of each component of our proposed bubble routing (BR) scheme, we first provide the big picture of BR architecture and design principles. As shown in Fig.5, BR consists of 5 main components as follows:

**(1) Prediction-based bubble management:** The ROB of each bubble runs AI algorithms (LSTM+GCN+GAN) to predict the next-time snapshot of the entire bubble, including each member's state parameters (position, link qualities, etc.). Each ROB shares information with neighboring ROBs.

**(2) Rough-to-Fine path seeking:** To quickly form a bubble chain to reach the destination bubble (B4 in Fig.5), we adopt a rough-to-fine path seeking process. In the first stage, BR scheme decides which bubbles should be included in the route chain. This generates a *rough* data path. In the second stage, each ROB determines the detailed *intra-bubble* links in its bubble. The source bubble favors the bubble chain with less bubbles, but also considers the impacts of congestion heat map, link distance, multi-route intersection issue, and altitude levels. It attempts to avoid the low-altitude and congested bubbles.

**(3) Using THz link 'bundle' to handle altitude-selective THz characteristics:** As shown in Fig. 5, for some inter-bubble communications, we can establish multiple THz links for the same route. Those links are called THz *bundle,* which is helpful to achieve load balance in different altitudes. For example, we may just need a single link between high-altitude bubbles since THz channel quality is high there. But we may need to establish multiple links for the low-altitude bubbles, to achieve the load-balanced transmissions (such that the lower altitude bubbles will not become the traffic bottleneck of the entire path).

**(4) Congestion-aware routing:** THz transmissions can easily cause queue overflow (and thus congestion occurs). This is the reason that all intra-/inter-bubble links should carefully coordinate their Tx/Rx schedules, antenna alignment, and data rate settings. In the routing layer, the new path should avoid the seriously congested bubbles or nodes. We will build a *traffic heat map* (THM) to reflect the load distribution/queue status in different regions. The light-traffic bubbles are preferred in the route chain.

**(5) Multi-pair route intersection issue:** There may be multiple paths between different source/destination pairs. Some bubbles may be the intersection places for two (or more) paths. In Fig.5 we have shown two communication pairs' paths (i.e., $S_1$-$D_1$, $S_2$-$D_2$), and B2 is the intersection bubble. Note that the boundary nodes of each bubble are responsible for the inter-bubble links. It is preferable that distinct boundary nodes are used for different paths' links since any intersection node can cause ¼-duplex issue.

Later on we will provide the details of the above 5 components. Here in Table 1 we first provide the main protocol of BR scheme. It controls the main operations during bubble chain establishment.

**Table 1.** Bubble Routing (Main Protocol)

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**Protocol 1: Bubble Routing (Main Program)**
**INPUT:** Bubbles' topologies in different altitudes, group missions/mobility modes, nodes' positions/velocities, available THz windows, source node/bubble, destination node/bubble
**OUTPUT:** The source-to-destination bubble chain with optimal THz communication performance (high-throughput, low packet loss rate, high path stability, low delay)
**Protocol operations:**

*Bubble forming & management *\

- Nodes claim the same bubble ID when they execute the same mission and similar mobility modes
- Use social network's centrality/betweenness concept to select ROB of each bubble
- All members of the same bubble report their status (position, velocity, titling angle, etc.) to ROB
- ROB manages bubble:
  i. Bubble floats: There is no member change and the ROB broadcasts its entire bubble movement trend to neighboring bubbles for bubble chain forming;
  ii. Grow: new member joins;
  iii. Shrink: a member leaves;
  iv. Merge: two bubbles become one if they are too close and have similar floating pattern; A new ROB will be selected
  v. Bubble Bursts: One bubble breaks into multiple ones due to mission change or mobility discrepancy. ROB may be re-selected if the topology changes a lot

*AI-based Bubble 'state' prediction *\

- ROB collects snapshots of the topologies for the historical time slices. Then, each of them uses graph model (vertexes & links) to represent the topology of each time slice. Graph data (network snapshots) are saved in First-in-Last-Out buffer. Buffer data will be inputted into LSTM+GCN+GAN model for online training to obtain spatial-temporal evolutionary patterns.
- ROB runs LSTM+GCN+GAN to predict the topology graph of the next time slice.
- ROBs in neighboring bubbles exchange their predicted results.

*Rough-to-fine Path Seeking*\

- Each ROB shares its floating state (position, trend, link states, etc.) with other ROBs in the neighboring bubbles. Each ROB maintains the neighbor bubbles' states.
- The source ROB seeks and obtains all possible bubble paths towards the destination bubble by depth-first search.
- By applying congestion- and altitude-aware route adjustment, the minimum cost path will be selected.

*Rough Path Seeking: Altitude-aware route adjustment*\

- Each ROB records the queue status of all of its members. It records the current queue size as well as filling rate.
- The ROB builds a traffic heat map based on the congestion level of each node, and also saves the information into First-in-Last-out buffer to marks out the trend.
- The source ROB filters out the paths with seriously congested bubbles.

*Rough Path Seeking: Altitude-aware route adjustment*\

- The source ROB collects the altitude and THz bandwidth information from each bubble.
- The source ROB determines the bottleneck places for each

rough bubble path based on the maximum capacity of each bundle. Each bundle may contain multiple links to connect two bubbles. The bundle capacity is calculated as the sum of all non-interference links.

*Handle intra-bubble routing *\

- Each ROB uses LSTM+GCN+GAN to estimate the next-time bubble topology (links states, etc.). It then determines whether to use (1) direct THz link from an input boundary node to an output boundary node; (2) use an internal bubble node to serve as THz relay between input/output nodes; (3) split the traffic into multipaths if a single path can't handle the large traffic rate.

*Handle multi-pair intersection issue*\

- If multiple pairs need to establish paths, each source bubble uses Rough Path Seeking to determine the involved bubbles.
- If a bubble needs to serve as the intersection between two paths, the bubble needs to coordinate among the boundary nodes to establish separate THz links.
- The two source ROBs negotiate a wave-like Tx/Rx schedule for their paths. Particularly the intersection bubble determines the Tx/Rx schedule for all boundary nodes' THz links.

### *D. Bubble Management*

*1) **Bubble formation and ROB selection** :* We use the social network metrics, centrality, to select ROB. The degree of centrality of a node measures the number of nodes that are connected to this node. A node with a higher degree of centrality has a higher chance to enable all nodes in bubble to establish THz links (either directly or indirectly). Generally, ROB is supposed to have the highest *degree of centrality* to serve as the relay node. Assume that $a(p_i,p_k)=1$ if a direct link exists between $p_i$ and $p_k$, and $a(p_i,p_k)=0$ otherwise, where *a* is the degree level, i.e., the number of adjacent nodes for a reference node. *Degree of centrality* for a given node $p_i$, can be calculated as [17]:

$$C(p_i) = \sum_{j=1}^{N} a(p_i, p_j) \tag{2}$$

Another related social network metric is called *betweenness centrality* (BC). A node with a higher betweenness in social network means that it can connect more pairs of nodes [18]. From a network viewpoint, it is a measure of the extent to which a node has the control over the information flow among other nodes. Denote $g_{jk}$ as the total number of geodesic paths linking $p_j$ and $p_k$, and $g_{jk}$ as the number of those geodesic paths with $p_i$. Then BC can be defined as:

$$BC(p_i) = \sum_{j=1}^{N} \sum_{k=1}^{j-1} \frac{g_{jk}(p_i)}{(g_j k)} \tag{3}$$

Fig. 6(1) shows a bubble example. Here the boundary nodes can be easily identified once a ROB is determined. For example, a ROB may use *unit ball fitting* (UBF) algorithm [19] to detect all nodes located on the boundary of the bubble. A boundary node may directly build a THz link with another boundary node, or it can use an *inner node* (including the ROB itself) to serve as the relay. In Fig. 6(2) and (3) we have also shown the difference between closeness centrality and BC.

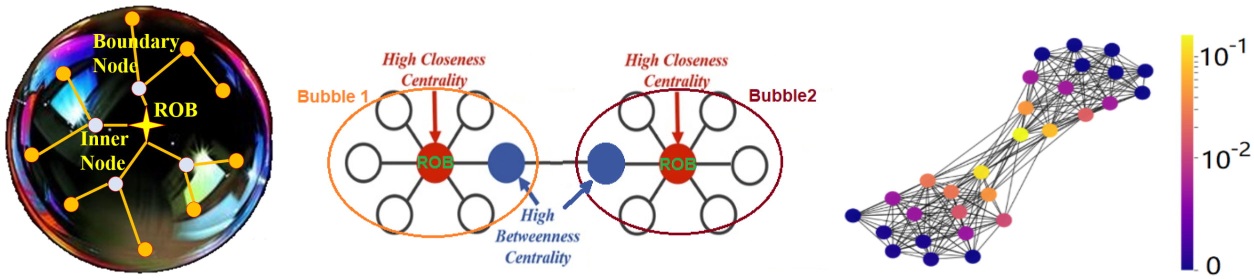
The steps of forming bubbles and selecting ROBs are shown in Sub-protocol 1 below (it can be called by the above main protocol).

**Table 2.** Bubble Formation and ROB Selection

**Sub-Protocol 1 (called by main protocol): Bubble formation and ROB selection**
**INPUT:** Node positions/velocity, sub-group missions/mobility modes, link qualities
**OUTPUT:** Different bubble IDs and ROB selection results
**Protocol operation:**
*Bubble forming *\
- Each node broadcasts its mission ID, coverage, mobility pattern (trajectory shape, mobility model, etc.), and link qualities.
- Nodes that have same mission ID, similar mobility patterns, and close to each other belong to the same bubble; Each node records all nodes in the same bubble in its Bubble table. Bubble ID is named by the node with the largest node ID.
- Besides Bubble Table, each node also maintains direct (1-hop) neighbor table.
- Based on the 1-hop neighbor list N(S) of node S, for every neighbor $X_1$, $X_2$, $X_3$,...,$X_n$ in N(S), we combine the neighbor lists as:
$M=N(X_1)\cup N(X_2)\cup N(X_3)\cup ...\cup N(X_n)$ Then for any node in M but not belonging to N(S), the node is classified into $N_2(S)$, which means that it is a 2-hop neighbor of S.
*ROB selection *\
- For each node *i* in N(S), based on the calculation of *degree of centrality* (see eq(2)), it selects the node with a degree greater than a preset threshold $D_{min}$, and adds this node to a set *C(S)* , which is the high-degree neighbors of node S. We can select the node with the greatest closeness centrality as the ROB.
- For each node j in N(S), considering all the links between node S and its 2-hop neighbors in N2(S), we calculate the result of *betweenness centrality* based on eq (3). Nodes with high betweenness levels are the boundary nodes that can be utilized to establish bundles between bubbles.
- ROB builds the graph model (called a snapshot) based on its members' connectivity status.

*2) **Bubble membership management** :* Each ROB maintains the state information of its bubble (such as the member changes). A ROB broadcasts its 'floating' status (such as the movement trajectory of the entire bubble in the last M time intervals) to all neighboring ROBs.

There are mainly 4 cases for member changes (Fig.7) : (1) *Grow*: A new node may join a bubble if it carries the same mission and closely moves with the entire bubble; (2) *Shrink*: A node shows different mobility pattern and gets further and further away from others. (3) *Merge*: Two close bubbles may merge into one if they show similar mobility pattern. (4) *Burst*: A bubble may burst out if part of the bubble




(1) A Bubble (2) Different Centrality Metrics (3) Betweenness Centrality

Fig. 6: Social metric-based ROB selection

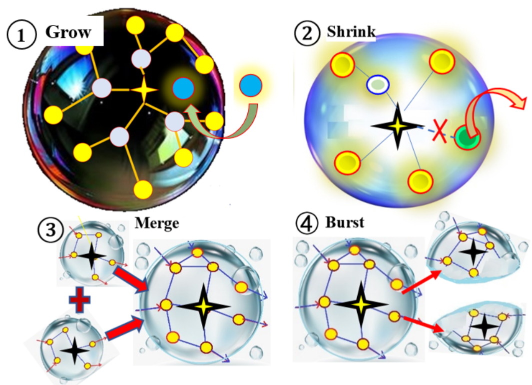



Fig. 7: Bubble member changes

leaves the entire body. Each bubble needs to determine new ROBs. Sub-protocol 2 shows the process of handling the above membership changes.

**Table 3.** Bubble membership management

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**Sub-Protocol 2 (called by the main protocol): Handle member changes in a bubble**
**INPUT:** The members' connectivity in a bubble, ROB ID, the graph of the topology in the bubble
**OUTPUT:** The latest graph of the bubble topology
**Protocol operations:**
*ROB information sharing *\
- Each ROB captures the entire topology and summarizes the entire bubble's movement trajectory
- Each ROB broadcasts its bubble trajectory in the last M time instants to all neighboring ROBs
- If a path passes through the current bubble, to reduce protocol overhead, the ROB only broadcasts the bubble trajectory to its in-the-route bubbles (such as upstream and downstream bubbles).
- Each ROB also reports its boundary nodes' status (positions, current traffic, queue, etc.)
*Bubble grows *\
- A boundary node detects an approaching non-member node and records its trajectory.
- The coming non-member broadcasts MISSION_ID and TRAJECTORY message (that holds the last M positions of the node). Once a boundary node receives it, it reports back to its ROB.
- If ROB finds a mission and mobility match, it sends INVITE message to the non-member and tells it about its direct connector (the member closest to it). Then the new node joins as a bubble member.
*Bubble shrinks *\
- A member is assigned with a new mission and sends LEAVE to the ROB along the tree branch.
- The ROB notifies the rest on the new connectivity of the entire bubble
*Bubble merge *\
- A ROB notifies a neighboring ROB that it was assigned with the same mission ID.
- Two ROBs exchange their topology information and determine the new ROB.
*Bubble burst *\
- The ROB detects the big mobility discrepancy of a subgroup of the bubble; or a subgroup of members all send out request of NEW_MISSION. The ROB approves the split and triggers new ROB selection process.

---

*3) Bubble Snapshot Prediction:* As we mentioned above, a ROB always maintains the historical snapshots (up to M time instances) of the entire bubble. This serves two purposes: First, it detects any member with a trend of leaving. Second, it uses such M snapshots for the next-time topology prediction. *The benefits of using M-snapshots-based prediction include four aspects:*

(1) Temporal trend capture: The bubble topology will not change abruptly since it is mission-driven and has coherent mobility modes. To accurately predict the next-time topology, we need to capture the time-varying patterns (for example, a boundary node moves slowly towards the inner position, a boundary node is leaving the range of the whole bubble, etc.). Such a temporal trend helps to predict a possible link outage or the leaving of a boundary node that is participating in an inter-bubble transmission.
(2) Spatial relationship evolution: The relative positions of different nodes can tell the possibility of building direct boundary-to-boundary (b2b) THz links inside a bubble or using an in-bubble node as the relay between two boundary nodes. Such a spatial layout determines the connectivity of the entire bubble. Therefore, the spatial evolution needs to be captured.
(3) Early Preparation for THz node coordination for both intra-/inter-bubble links: When we can use historical snapshots to predict the next-time bubble topology, we can prepare for any antenna misalignment due to node movement, or even change THz communication bands

since THz channel is distance-/altitude-selective. Early preparation is critical to THz communications to avoid huge packet loss.

(4) Congestion Awareness: We define the concept of Traffic Heat Map (THM) (details in section 3.4.2) to reflect traffic distribution in the network. M-snapshots-based prediction provides us the trend of THM evolution and helps to find a congestion-avoided bubble chain (the entire route consisting of a series of bubbles).

**Prediction Model:** We propose to use LSTM+GCN+GAN model (Fig. 8) to achieve large-scale, spatial-temporal *topology + state* (T+S) prediction for each bubble. Such a model can adapt to the dynamic network topology [20]. However, unlike [20] that assumes the entire path consists of single nodes, here we will define new feature matrix for *bubble*-based (T+S) prediction, including (1) topology information (such as the node connectivity, bubble membership, etc.), and (2) state of each node/link (such as position, velocity, link quality, etc.). We use *connectivity matrix* $C$ to represent topology information and use *feature matrix* $F$ to represent the state of nodes/links. We define the matrix $C$ as:

$$C = \begin{bmatrix} C_{11} & \dots & C_{1n} \\ \vdots & \ddots & \vdots \\ C_{n1} & \dots & C_{nn} \end{bmatrix}$$

where, the element $c_{ij}$ in row $i$ and column $j$ is equal to 1 if there is a link between node $i$ and $j$. Otherwise, $c_{ij}$=0. Feature matrix $F$ is expressed as

$$F = \begin{bmatrix} f_{11} & \dots & f_{1n} \\ \vdots & \ddots & \vdots \\ f_{n1} & \dots & f_{nn} \end{bmatrix}$$

In our implementation, element $f_{ij}$ in row $i$ and column $j$ is further written as:

$$f_{ij} = Cap(z_i, z_j, d_{ij})/max(\mathcal{E}_i, \mathcal{E}_j) \tag{4}$$

Here, $Cap(z_i, z_j, d_{ij})$ denotes the estimated link capacity based on nodes' altitude ($z_i \, and \, z_j$), as well as the distance $d_{ij}$. In addition, $\mathcal{E}_i$ and $\mathcal{E}_j$ indicate traffic heat map (THM) values at the locations of nodes $i$ and $j$. $\mathcal{E}$ is a normalized value with a range from 1(the least congested) to the maximum threshold $\mathcal{E}_{max}$ (the most congested). The expression for $f_{ij}$ gives a measurement for maximum link quality. Each single network snapshot A contains bundle connectivity matrix $C$ and feature matrix $F$.

Given a bubble's previous $T$ snapshots, $A_{\tau-T}, A_{\tau-T+1}, \cdots, A_{\tau-1}$, as well as the current snapshot $A_\tau$, the ROB will predict the next snapshot as follows:

$$\overline{A_\tau} = f(A_{\tau-T}, A_{\tau-T+1}, \dots, A_{\tau-1}) \tag{5}$$

*here f(.) is a nonlinear function of DL model.*

We feed $\mathbf{C}$ and $\mathbf{F}$ to LSTM-GCN (graphical convolutional network). To generates the output ($\mathbf{Y}$):

$$\begin{aligned} \mathbf{T} &= LSTM - GCN(\mathbf{C}, \mathbf{F}) \\ &= g(\mathbf{W} \cdot \mathbf{F} \cdot (\widehat{\mathbf{D}}^{-\frac{1}{2}}(\mathbf{C} + \mathbf{I_N})\widehat{\mathbf{D}}^{-\frac{1}{2}}) \end{aligned} \tag{6}$$

where LSTM-GCN is the DL model, $g(.)$ is the activation function, $\mathbf{W}$ is the weight matrix of the DNN, each element of $\mathbf{D}$ has the format of $\widehat{\mathbf{D_{ii}}} = \sum_{j=1}^{N} \widehat{\mathbf{C_{ij}}}, and \ \widehat{\mathbf{D}}^{-\frac{1}{2}}(\mathbf{C} + \mathbf{I_N})\mathbf{D}^{-\frac{1}{2}}$ is the approximated filter of GCN. Here $\mathbf{I_N}$ is the N-dimensional identify matrix.

LSTM is typically trained by using the mean square error (MSE) loss function. However, MSE cannot handle the matrix sparsity issue [20]. The connection matrix $\mathbf{C}$ may have sparsity nature since not all bubble nodes have direct connectivity between them. MSE also cannot well handle the wide value range issue. The feature matrix $\mathbf{F}$ may have a wide scope of values.

To overcome the above three issues, here we use GAN with adversarial training to 'push' the generator ($\mathbf{G}$) (from LSTM-GCN) to keep improving its prediction accuracy by using the discriminator ($\mathbf{D}$). Here D alternatively takes G's output ($\overline{A_\tau}$) or the ground-truth $A_\tau$ as the input.

The concrete protocol for the above deep-learning-based bubble state prediction model is shown in Table 4.

**Table 4.** Bubble (T+S) prediction

**Sub-Protocol 3 (called by the main protocol): predict the next-time bubble state**

**INPUT:** The members' connectivity in a bubble, ROB ID, the snapshot graph of the topology in the bubble

**OUTPUT:** The predicted next-time bubble topology & state (T+S)

**Protocol operations:**

1. ROB records the topology and state (T+S) of each node/THz link, in each time slice (30ms each slice)
2. ROB constructs a graph based on the snapshot; The graph consists (V,E) with C & F matrices. (assume that LSTM-DL 'training' can be performed offline based on empirical data sets obtained in history)
3. ROB stores the historical T snapshots and runs LSTM+GCN+GAN algorithm to predict the next-time snapshot.
4. ROBs exchanges predicted snapshot (with (T+S) outcomes) with neighboring ROBs for inter-bubble coordination.
5. ROBs uses predicted snapshot to manage bubble membership.
6. The ground-truth snapshot is used for next-time algorithm iteration (used in GAN's discriminator).

*E. **Intra-Bubble THz Links: Coordination within the same bubble***

*1) **Inside Bubble: Achieve stable neighborhood THz transmissions**:* Since the nodes belonging to the same bubble have relatively stable links due to similar mobility modes, the

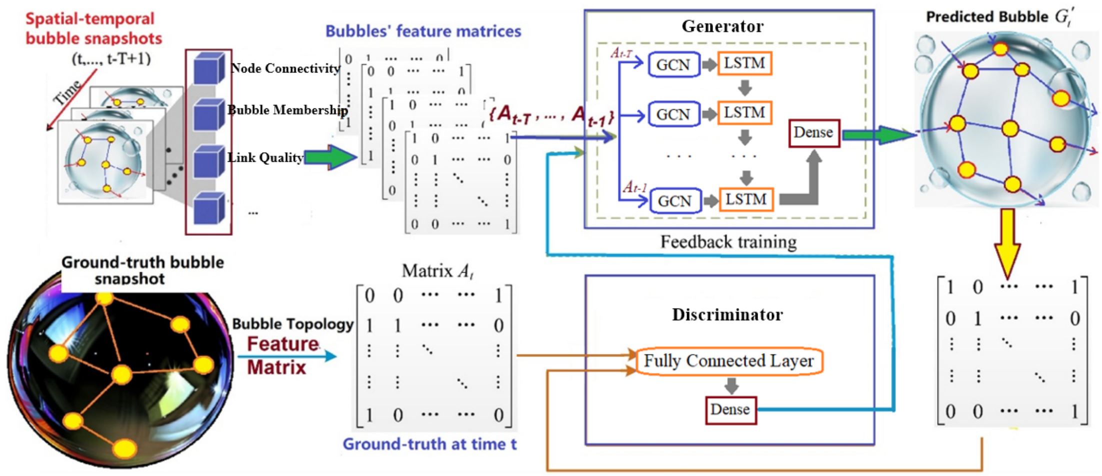
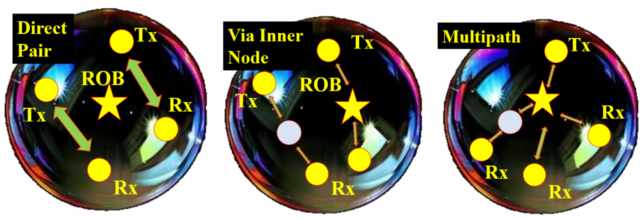



Fig. 8: Bubble topology evolution prediction




(1)Direct THz link (2)Relay via inner (3)One-to-multiple (1:M)

Fig. 9: Three intra-bubble cases

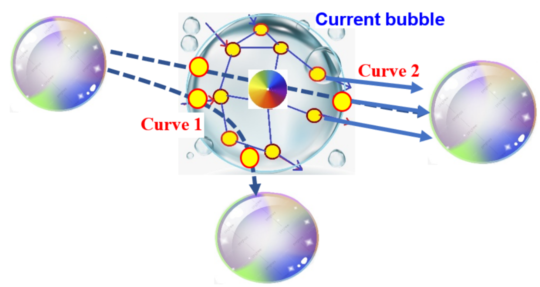



Fig. 10: Intra-bubble data forwarding: Direct or Relay-based

intra-bubble links' quality is higher than inter-bubble links. This means that we can achieve a higher data rate inside the bubble than the inter-bubble links. Generally, there can be 1 to 3 hops from an input to an output boundary node. Here we consider three data forwarding cases:

(1) Direct (1-hop) communications (Fig. 9(1)): An input boundary node (that is in the downstream direction from a source to a destination bubble) can directly send data to an output boundary node. This is the preferred case since it avoids the delay caused by any relay.

(2) Using inner node(s) for relay (Fig. 9(2)): If the bubble is large (>2 hops), THz channel will have large fading loss due to longer distance. Therefore, one or multiple inner nodes (or ROB itself) must be used to relay the data.

(3) Fusion case (Fig. 9(3)): Due to the environmental condition differences (such as humidity, altitudes, link distance, etc.), the input flow rate may be much higher (or slower) than the output flow rate for the same route. To balance the traffic loads in different locations, we may have one-to-many (1:M) links in the input/output nodes, as shown in Fig. 9(3). Here ROB helps relay data and splits the incoming traffic into three outgoing flows.

To coordinate the above 3 types of communications, the ROB will run the previous discussed LSTM+GCN+GAN algorithm to predict the snapshot of the next time interval for the entire bubble's $T$+$S$ (topology and node/link state). Based on the estimated snapshot, it will perform the following three tasks:

a) Determine one of the 3 intra-bubble cases: The ROB checks the network topology of the upstream and downstream bubbles in the entire end-to-end path. Dijkstra's algorithm can be used to find the shortest (lowest cost) bubble chain. If the flow rate does not overload the corresponding THz channel, a direct link or a relay-based link may be built (see Fig.10 curve 1). In other cases, a 1:M multipath structure (curve 2) is preferred by applying depth first search (DFS) method.

b) Notify bubble state: The ROB uses the predicted bubble state to schedule each node's role (Tx or Rx) and determine the THz band to be used in each link. It then sends the INTRA_INFO message to all bubble members. The INTRA_INFO has the message format as shown in Fig. 11. As we can see, it includes some critical packet fields such as relay mode (i.e., the 3 cases shown in Fig. 9), Tx/Rx role, how long it will transmit data (duration), which THz band to use, predicted node state (position, tilting angle), ground-truth node state in the previous time interval, upstream node ID (if it is an input boundary node, this ID refers to the upstream bubble's node), downstream ID (if this is an output boundary node, this ID refers to the node in the next bubble), and other fields (such as time-to-live (TTL), suggested queue length, etc.).

c) Runs intra-bubble protocol for each active in-bubble link: The ROB runs the intra-bubble protocol to manage *each active* in-bubble path section (one or multiple hops). It manages the coordination among input boundary node (Tx), output boundary node (Rx), relay node(s), and even backup node (which serves as a backup relay node if the original node cannot help to relay data due to sudden mobility change). Fig.12 shows the protocol

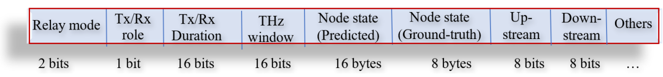



Fig. 11: INTRA˙INFO message format

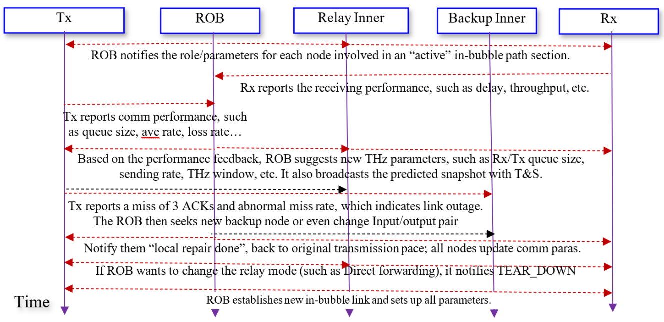



Fig. 12: Sub-Protocol 4: Intra-Bubble THz Transmission

message exchanges during intra-bubble transmissions.

2) ***Inside Bubble: Dynamic THz link management:*** Although intra-bubble nodes have coherent mobility, it is still possible that a link may have poor quality or even outage. The ROB then needs to perform the in-bubble repair under dynamic links. Here we provide the four typical link repair cases:

(1) Change relay inner node: Depending on the relative position/angle changes of either Tx or Rx node, the ROB may switch the relay node to a backup node, which should guarantee that the uplink and downlink have similar link quality and no other nodes block the THz signals.

(2) Change either Tx or Rx (or both): If the input boundary node (Tx) leaves, the ROB will immediately notify the upstream bubble's ROB and select a new input boundary node. If the output boundary node leaves, it negotiates with the downstream bubble's ROB to build a new inter-bubble link.

(3) Change transmission mode (direct, relay, or fusion mode, see Fig.9): Although the direct Tx-Rx link is preferred, such a link may be unavailable and a relay-based mode is thus needed. If the input and output nodes are under different communication conditions, the fusion mode may be used. The ROB determines how many branches the aggregated traffic will be distributed to.

(4) Change THz communication parameters (THz band, sending rate, queues size, Tx/Rx schedule, etc.): This could occur with the above three adjustments or be performed independently. First, the THz band may need to change since THz channel is both distance- and altitude-selective. Second, the THz transmission rate needs to be set up carefully, especially in fusion mode (Fig.9(3)), to avoid queue overflow in the Rx node. Third, the queue size should be properly adjusted (if it is too short, overflow can easily occur; if it is too long, the queueing delay is too long). Fourth, the Tx/Rx schedule should also be set up properly to avoid unnecessary idle (waiting) period. For example, when a downstream node's antenna switches to Rx mode, the upstream node's antenna is not ready for Tx mode yet.

Table 5 provides the protocol operations for the above dynamic in-bubble THz link adjustments.

**Table 5.** Dynamic in-bubble THz link management

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**Sub-Protocol 4 (called by the main protocol): Dynamic in-bubble management**

**INPUT:** Assigned routing tasks for the current bubble; the members' connectivity status in a bubble, ROB ID, the snapshot graph of the topology in the bubble

**OUTPUT:** The adjustment of in-bubble communication parameters/layout under bubble topology dynamics

**Protocol operations:**

*In Relay node - deal with link failure *\

- Relay node reports LINK_STATUS parameters (SNR, BER, etc.) to ROB.
- ROB makes next-time *T+S* prediction. If link failure will occur, ROB notifies Tx, Rx, and relay node
- ROB selects the best relay and sends REPLACEMENT to this new and old relay
- ROB sends new THz parameters (window, rate, queue, etc.) to Tx, Rx, new relay for each 'active' path

*Replacing boundary nodes *\

- If boundary nodes (input or output) leaves, the path section needs to find a backup node.
- ROB tried to find another nearby boundary node, and notifies other in-path nodes to achieve this change.
- The new boundary nodes are assigned with proper rate, queue, and join the DL-based monitoring plan.

*Mode transfer among direct, relay and fusion *\

- If a direct link exists, the relay-based links should be torn down and transfers to direct mode.
- During transfer, the ROB can hold the undelivered packets and re-deliver to new Rx of the new link.
- If transferring to relay-based mode, ROB will tell the suitable relay node as well as the transmission schedule (the relay node needs to switch to upstream and downstream alternatively.
- If transferring to fusion mode (1:M), the ROB itself or another inner node serve as the fusion center. ROB determines the schedule (when the center receives the input traffic, when the center switches one by one for the output flows.
- ROB use INTRA_INFO message to suggest proper buffer size for each node.

*THz parameters adjustment *\

- Based on the link distances, node altitudes, and current flow path information, the ROB determines suitable THz band and Tx/Rx schedule for each link pair.
- ROB provides the LSTM+GCN+GAN based *T+S* prediction results. Each pair of nodes adjust their antenna orientation to ensure good antenna alignment.
- ROB suggests the suitable sending rates for the sender based on THz bandwidth and QoS requirements
- The queue length is selected based on the traffic rate and queueing delay requirement

---

*3) **Overcome 1/4-deplex Issue:*** One of the benefits of using bubble concept is that it can address 1/4-duplex issue, which occurs when a node needs to help relay two pairs' routing flows. If it is a single node, this node needs to switch its beam for 4 times in a complete cycle (Fig.13). This makes it operate in 1/4-duplex mode and leaves each flow only half delivery time. This is the reason that in conventional ad hoc networks we should try to avoid the intersection of two paths.

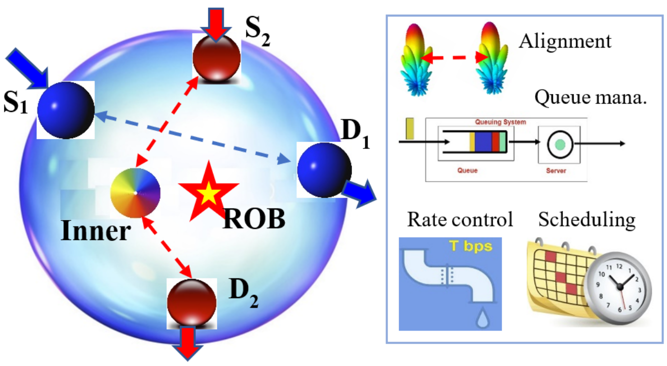



Fig. 13: Handle 1/4-duplex issue

However, in our bubble routing scheme this issue can be alleviated by using different nodes belonging to the same bubble. As shown in Fig.13, S1-D1 and S2-D2 are two different pairs without any intersection point between them. The ROB will coordinate the following 4 settings:

(1) *Antenna alignment:* ROB sends its predicted bubble *T+S* parameters to each active node. For example, if $S_1$ knows that $D_1$ will have aircraft tilting, it will adjust its antenna orientation. ROB can request that both Tx and Rx adjust their antenna properties (gain, beamwidth, etc.).

(2) *Queue management:* The allocation of proper queue size depends on THz rate and QoS requirements. We require that a Tx node should be able to hold at least 10ms of packets during multimedia communications. If the data rate is 100Gbps and packet size is 10K bytes (note that THz packet size should be larger than general Internet packet size (1500 bytes) to efficiently utilize the high THz bandwidth), then 10ms of data has 12,500 packets (1G bits). Note that in relay mode ($S_2 - D_2$), the relay node needs to adjust its queue length to match the Tx ($S_2$) and Rx ($D_2$). A higher rate often demands a large queue size.

(3) *Rate control:* The sending rate of Tx or relay node depends on the entire path's traffic amount and the upstream bubble's output link rate. We propose to use the above discussed bubble prediction results to adjust the data rate as below:

Predictive in-bubble rate control: Assume that the source bubble receives the state reports from all the ROBs of the path bubbles and decides to use an average sending rate of $R$ bps in the sender side. For a particular bubble $B_i$, assume that its input boundary node receives the data with the rate $R$, it can determine the in-bubble data rate as follows:

Suppose it is in *direct* mode (Fig.9(1)) (if it is a relay mode, the similar principle can be applied to determine

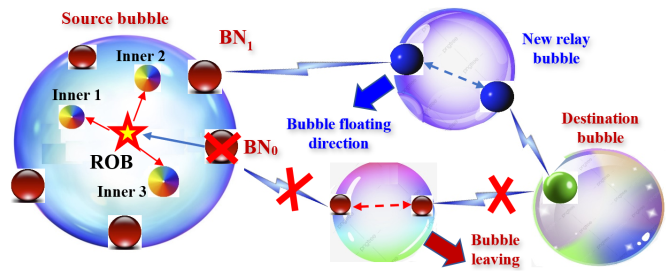



Fig. 14: Handle relay-bubble failure: Store-and-go

the sending rate based on the relay link's quality), it asks the *output boundary node* (OBN) to feedback its predicted inter-bubble link quality ($SNR_{out}$), which can be obtained by using the exchanged bubble ($T + S$) information between the ROB of the current bubble and that of the downstream bubble. The in-bubble link quality is measured by the $SNR_{in}$. Suppose that the OBN can use its buffer to handle $S$ bps of incoming data. Then the sending rate of the input boundary node (IBN) (to the OBN) can be set up as:

$$R_{IBN} = R \times SNR_{in}/SNR_{out} + S + \Delta R \qquad (7)$$

Here $\Delta R$ is an balance factor used to prevent large deviation of $R_{IBN}$ from $R$. It can be determined by using historical empirical data. For example, $\Delta R$ should be set up such that $|R_{IBN} - R| < 50\% \times R$

(4) *Scheduling:* The ROB will schedule the Tx/Rx time for all the through-bubble paths. To avoid the 1/4-duplex issue inside the bubble, all the paths should try to avoid intersection points in the bubble. To reduce the delay of the entire path, the direct mode should be used first. If the relay or fusion mode must be used, the ROB must schedule each node's Tx/Rx based on the entire path's delay requirements.

*4) **Inside Bubble: Store-and-Go for Congestion Absorption**:* The floating of each bubble may cause inter-bubble link failure, especially in sparse network (i.e., the entire FANET does not have enough bubbles to guarantee the inter-bubble link availability). To handle this issue, we require that each bubble has the capability of "store-and-go (SAG)". That is, each bubble may need to store the data for some time until a suitable new relay bubble is available (Fig.14).

Compared with conventional store-and-forward used in general ad hoc networks [21], our bubble routing provides a much better "packet absorption" capability since the buffered packets can be distributed into the entire bubble. As shown in Fig.14, suppose an OBN (BN$_0$) cannot deliver the packets to the next bubble that is floating away. Before a new relay bubble is detected, BN$_0$ stores the packets in its buffer. Then the ROB of the current bubble performs the operations as shown in Table 6.

**Table 6.** Store-and-go based in-bubble buffering to handle bubble failure

**Sub-Protocol 5 (called by the main protocol): In-bubble Store-and-go policy**

**INPUT:** Active path section in the current bubble, relay bubble's T&S, assigned routing tasks for the current bubble; the members' connectivity in a bubble, ROB ID, the snapshot graph of the topology in the bubble
**OUTPUT:** In-bubble store-and-go based data delivery
**Protocol operations**

(1) Check $BN_0$'s buffer capacity. If it is not enough for possible new coming packets, ROB notifies $BN_0$ to send partial packets to ROB itself.
(2) Depending on ROB's buffer capacity, ROB can further distribute the packets to other bubble members with much free queue space. Some boundary nodes are preferred since they can immediately forward to any available bubble.
(3) ROB immediately feeds back the RELAY_FAILURE message to the source bubble along reverse path.
(4) The source bubble pauses the transmission to avoid overwhelm of bubble's buffer.
(5) When a new bubble floats to the suitable position, current ROB negotiates with the new relay ROB on the establishment of in-bubble THz links to help forward the old data.
(6) If new inter-bubble links are established, the buffered packets go to new relay bubble. Meanwhile ROB reports the RELAY_AVAILABILITY to the source bubble to indicate the local path repair.

### F. Inter-Bubble THz Links: Coordination between bubbles

*1) **Altitude-aware Inter-Bubble THz Links**:* As mentioned before, THz link is not only distance-selective, but also altitude-selective. In airborne networks, the aircraft may fly across a large altitude range (1-15 km). THz bands have very different fading loss levels in different altitude levels. As shown in Fig.15, here X-axis is the THz frequency range (0.1-10 THz), Y-axis is altitude, the blue areas represent the good communication conditions (with small fading loss) and the red areas mean serious fading loss. As we can see, when the altitude is less than 2 km, only [0.1-1 THz] can be used without much fading loss. When the altitude is >6 km, more bandwidth in higher THz frequency can be used. Between 2-6 km, we can use some sporadic high-frequency bands. This is mainly due to THz signals' vulnerability to tiny objects (such as raindrops). Higher altitude of sky has less cloud and thus has better THz signal propagation effect.

Many conventional ad-hoc routing protocols use multi-path architecture. They either use single link in each hop (i.e., the path passes through each single node) or multiple paths between the source and destination (but each hop still has one link). Such a multi-path architecture may not be suitable to a THz-based FANET across a large altitude range. This is due to the above THz's altitude selectivity. Higher altitude links may use higher THz carrier frequency and thus occupy a wider bandwidth since high-frequency THz links do not have much channel fading loss in higher altitudes. Based on Shannon Theorem, in higher altitude a wider bandwidth means that a higher sending rate could be achieved

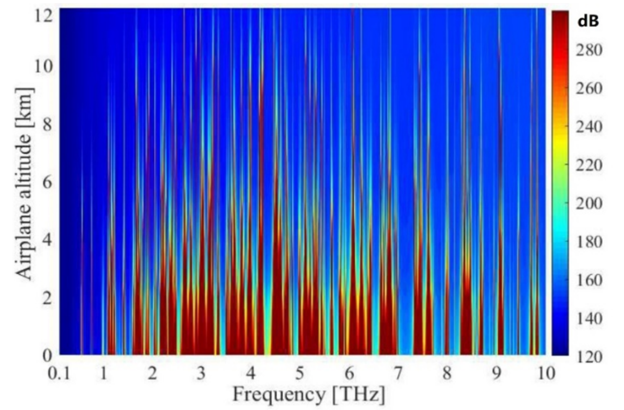


Fig. 15: Altitude-selective THz performance [9]

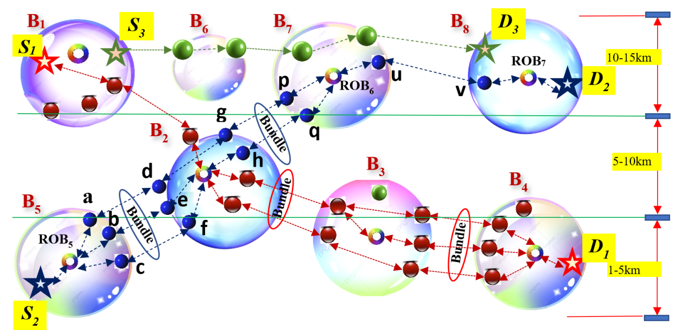


Fig. 16: Altitude-aware inter-bubble communication

If the source and destination bubbles are located in different altitudes, we propose to use different "path thickness" levels for inter-bubble links. The concept of bubbles is beneficial to such an "uneven" route establishment. As shown in Fig.16, there are 3 pairs of source/destination bubbles: $S_1$-$D_1$, $S_2$-$D_2$, $S_3$-$D_3$. They represent different altitude cases. Here we use $S_2$-$D_2$ pair (across low and high altitudes) as an example: The source node $S_2$ is located in the source bubble $B_5$, and the destination $D_2$ is located in $B_8$. Suppose the targeted average data rate is 100 Gbps.

$S_2$-$D_2$ path passes through $B_5$, $B_2$, $B_7$ and $B_8$. Since $B_7$ and $B_8$ are both in high altitude levels, we may just need a single inter-bubble link $(u-v)$ to deliver 100Gbps of data. However, between $B_2$ and $B_7$, due to the decrease of the altitude (thus less bandwidth), we may need to establish two inter-bubble links $(g-pandh-q)$ to keep the smooth traffic flow across all bubbles. Just a recall here, we named the links between B2 and B7 as "THz bundle" before. Here each link has approximately 60 Gbps of data rate. Likewise, in low altitude (between $B_5$ and $B_2$), we need even a thicker THz bundle, which could consist of 3 parallel links $(a-d, b-e, c-f)$, each with a data rate of $\sim 30$ Gbps.

$S_1$-$D_1$ path also has THz bundles in low and medium altitudes. For another pair ($S_3$-$D_3$), we just need a single THz link everywhere since all bubbles are in high altitude.

The inter-bubble communication protocol details are shown in Table 7.

**Table 7.** Altitude-aware inter-bubble communications: THz bundle control

**Sub-Protocol 6 (called by the main protocol): Inter-bubble**

**bundle control**
**INPUT:** Involved bubbles in the path, each relay bubble's T&S, the snapshot graph of the topology in the bubble
**OUTPUT:** Established THz bundles between bubbles
**Protocol operations:**

(1) ROBs exchange their snapshots (current and predicted). Each ROB share current THz bundles with others.
(2) Two ROBs designate the boundary nodes that will participate in the bundle. Those nodes are able to establish parallel links and are within direct LOS (line of sight).
(3) Antenna alignment: The ROBs must notify the buddle nodes on the predicted node/link state (via DL algorithm) such that the nodes can adjust their antenna beam to face each other well. The THz window may be changed.
(4) Rate setup: The upstream bubble's boundary nodes choose rates as follows:
Assume the source bubble's total sending rate is R bps, if the current bubble thickness is 3, then each link has the rate of around R/3. However, each link can adjust its rate slightly based on its link quality as follows:

$$R_i = R/3 \pm \Delta R, \ and \ \Delta R - SNR$$

(5) Queue setup: Each node sets up queue size based on two factors: (a) Total link rate. A higher rate desires a longer queue. (2) Queueing delay: A lower delay requires a shorter queue.
(6) Schedule setup: The fusion center (typically the ROB, or an inner node) switches its Tx (or Rx) between the bundle links in turn. It also splits the traffic evenly between links.

*2) End-to-end path seeking to construct bubble chain: Heat-map-based route establishment:* Because THz communications are sensitive to link stability, we need to search a path (consisting of a chain of bubbles) with good stability during the entire transmission session that may last 100 ms∼100 s for most tasks. Besides the bubble mobility, the ultra high THz rate means that a node could easily get congested if its packets cannot be cleared up in a timely manner. If most nodes of a bubble are congested, this bubble may not be able to help with a new path anymore. Therefore, we propose a *THM*-based path seeking strategy, which requires that each ROB adds nodes' *queue* information to the snapshot of its topology when it performs deep learning (DL)-based T&S prediction.

The THM (Fig. 17(b) & (c)) is defined as a heatmap with a size of $X \times Y$. Where, $X$ and $Y$ are width and height of the THM. They indicate the resolution of the map. The heatmap value $\mathcal{E}(x, y)$ at position $(x, y)$ is defined as:

$$\mathcal{E}(x, y) = \frac{\sum_k \varphi_k}{Cap_{max}} \times \frac{\sum_i b_i}{\sum_i B_i} \quad (8)$$

The term $\sum_k \varphi_k$ represents the sum of each flow (ID=$k$)'s data rate, $Cap_{max}$ is the maximum channel capacity at that place; $\sum_i b_i$ is the sum of queue sizes, $\sum_i B_i$ indicates total available queue size for the nodes located at $(x, y)$. Note that $\frac{\sum_i b_i}{\sum_i B_i} = 1$ if there is no node located at position $(x, y)$.

The idea of THM (Fig 17 (b) & (c)) is very similar to city traffic map shown in Fig. 17(a). Each pixel value in the THM represents the traffic level of the THz channels.

To implement the above idea of THM, the ROB will monitor two parameters:

(1) Current THM: The queue filling status is marked out in the graph model of the bubble topology. If the queue enters RED zone, that means that more than 80% of its queue is filled up and the queue may drop any new coming packets. It the queue size ∼ 20%, it is in GREEN zone. Other congestion levels are also defined for fine-resolution routing control.

(2) THM trend: ROB uses the (T+S) prediction model to predict traffic density changes in each node of each bubble.

A bubble can become a relay bubble of a path only when the following two conditions are met: (1) The bubble can provide at least an in-bubble path (either directed, relay-based, or fusion-based) with some nodes not in RED zone; (2) The potential in-bubble path nodes do not have a changing trend that could cause it to enter RED zone before the communication session ends.

Therefore, when the source bubble seeks the best path (i.e., a bubble chain), it will consider both bubble mobility and the traffic congestion level. Using Fig. 18 as an example, although S-A-B has the lowest hop count, bubble A has the serious congestion. It thus cannot be served as a relay bubble. S-B-C-D is another choice. but bubble B is unstable and tends to float away. The S-E-F-G-D is the best path since it has the least congestion level in each bubble and all bubbles are relatively stable during the transmission period. Moreover, since the THz channel is altitude-sensitive, a path with a higher altitude has more stable links.

## IV. Performance Analysis

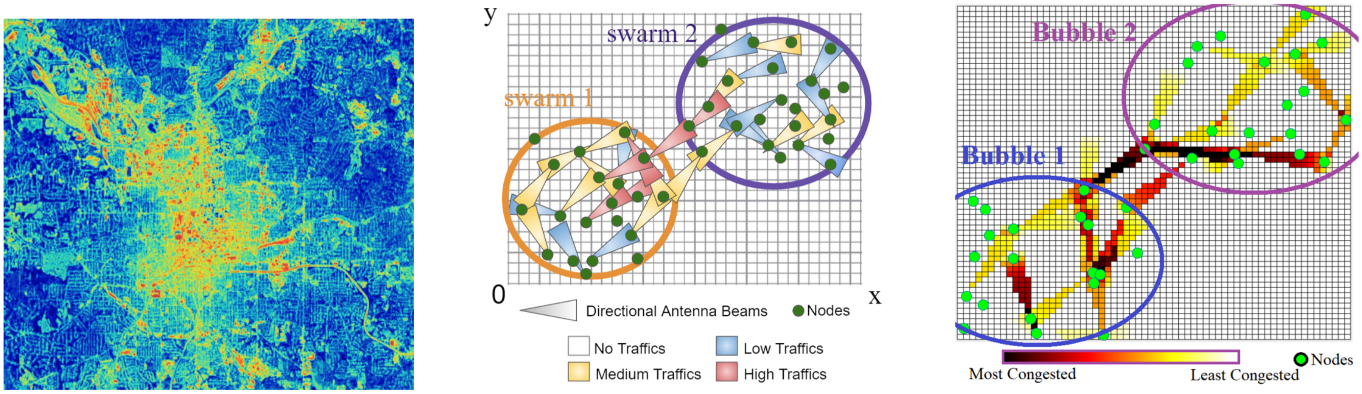
### A. Bubble Formation

Figure 19 shows the simulated network architecture after applying the above discussed bubble formation and ROB selection protocol. The bubble merging and bursting process is shown in Fig. 20. Two bubbles (IDs = 0 and 2) at the top merge into a large bubble at first. Then, the merged bubble bursts into two smaller ones at last.

### B. Bubble Routing Process

To illustrate the effect of bubble routing, a network with over 100 nodes was simulated. Fig. 21 shows our test scenario. Here all links with the distance of less than 3500 m are shown in the dashed lines (means there are RF links there). Also, the congestion areas are highlighted with different colors. Fig. 22 shows the path found by using the shortest path-based routing scheme, i.e., ad hoc on-demand vector (AODV). Such a routing scheme ignores the THz channel properties as well as the congestion distribution.

Fig. 23 shows the use of AODV in bubble-based network architecture. First, each bubble is seen as a single node in the AODV protocol. The bubble chain is thus found with the least number of bubbles from the source to destination bubble. Then AODV is executed inside each bubble to identify the shortest in-bubble path. However, AODV-generated path could




(a) City Traffic Map. (b) Concept of THz Traffic Heat Map. (c) Simulated THM.

Fig. 17: Traffic heatmap of bubble routing

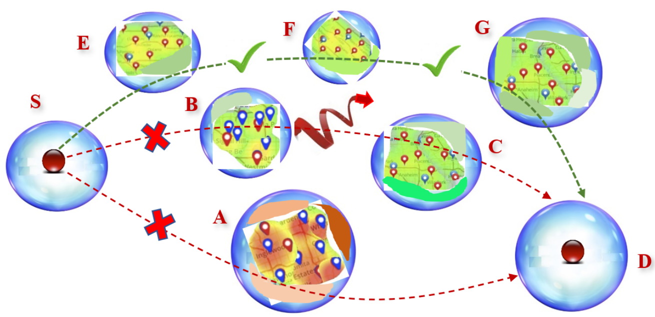



Fig. 18: Heat-map-based end-to-end path seeking

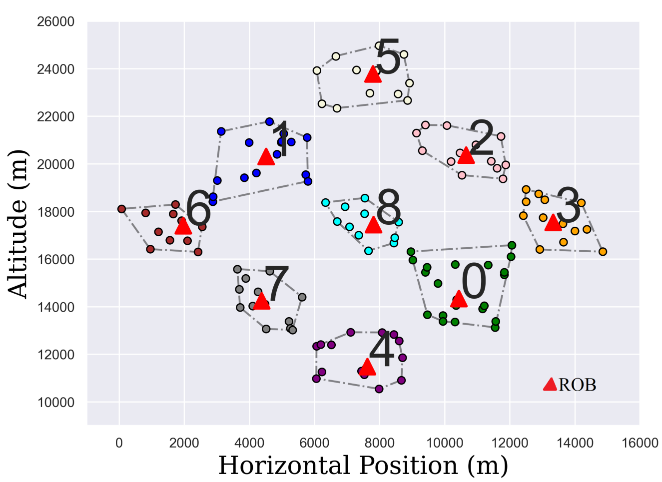



Fig. 19: Bubble-based FANET architecture. (Bubble IDs are Highlighted)

still pass through the highly congested areas. Moreover, it fully ignores the altitude-selective THz channel properties.

In contrast, our bubble routing scheme can avoid the congested bubbles and finds a route towards the higher altitude (Fig. 24). To avoid traffic bottleneck in the entire bubble chain, it can generate multiple paths among the bubbles at the lower altitudes. Those paths consist of multiple inter-bubble links between the boundary nodes. Those paths merge into a single path at the higher altitude levels.

## C. QoS Performance

We verify the QoS performance of protocols by using a discrete-event-based simulator built by Python. Our simulator includes the following components: (1) THz channel models, (2) propagation model, (3) link layer channel access control, (4) deep-learning-based routing protocol.

The simulation parameters are listed in Table 8. The antenna parameters followed [22]. We have considered different altitude levels (from 10 km to 25 km). We have also implemented the THz channel model which is an approximate linear version of the model in [23]. Each node follows Gaussian Markov mobility model with its maximum turning angle restricted. Center bubble (bubble #8) is assumed to have high traffic density (thus it is a highly congested bubble). The source node is in bubble 7 and the destination node is in bubble 2. Multiple tests were done with changing source/destination nodes (but the source/destination bubbles do not change).

Five routing schemes are compared in our simulations: (1) general AODV scheme applied to each individual node, (2) AODV applied to bubble structure (i.e., seeing each bubble as a virtual node), (3) general OLSR protocol. (4) the BDT protocol proposed by Qing et al [14]. It is an adaptive Q-learning based routing protocol. BDT tries to optimize the route by adjusting the buffer occupancy rate on each node. (5) our bubble routing scheme. The throughout result without and with the use of (LSTM+GCN+GAN)-based prediction algorithm are shown in Fig. 25 and Fig. 26, respectively. They demonstrate that bubble routing outperforms other 4 routing schemes. Its throughput can reach 400 Gbps with prediction algorithm and 300 Gbps without predictions. While the maximum throughput of BDT without prediction is around 200 Gbps since does not consider the ¼ duplex issues. Recall that the maximum 1/4-duplex link traffic speed is around 250 Gbps. OLSR and AODV choose the route with the lowest hop count and quickly encounter congestion issues because they enter the heavy-traffic areas. OLSR and AODV's maximum throughput is around 100 Gbps without prediction and 200 Gbps with prediction.

The delay performance without and with prediction algorithm is shown in Fig. 27 and Fig. 28 respectively. Delays for the AODV and OLSR cases increase fast even at the beginning stage and finally are more than 400 ms. In contrast, the delay for bubble routing with predication increases more

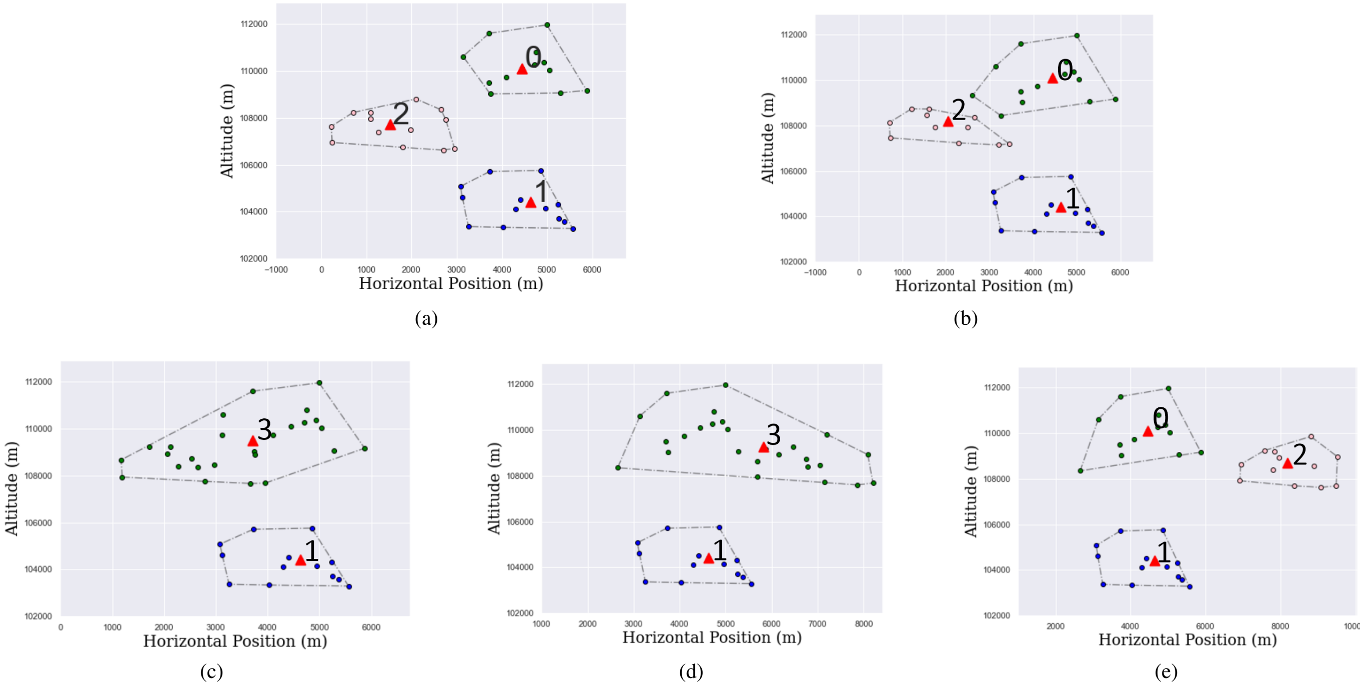



Fig. 20: Bubble evolution (Mean node mobility speed = 141m/s). (a) T= 0s. Initial State; (b) T=7s. Bubble 2 moves forward to Bubble 0; (c) T =10s. Bubbles 2 and 0 Merge. (d) T = 25s. Large bubble starts to burst. (e) T=30s. The large bubble bursts into 2 smaller ones.

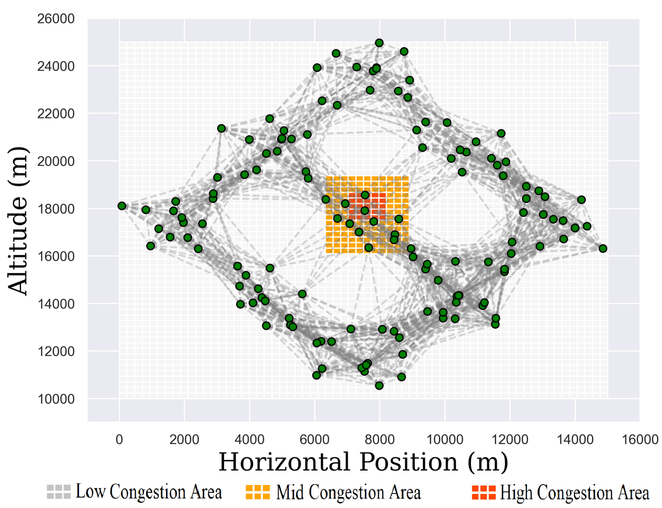



Fig. 21: Simulation Topology.

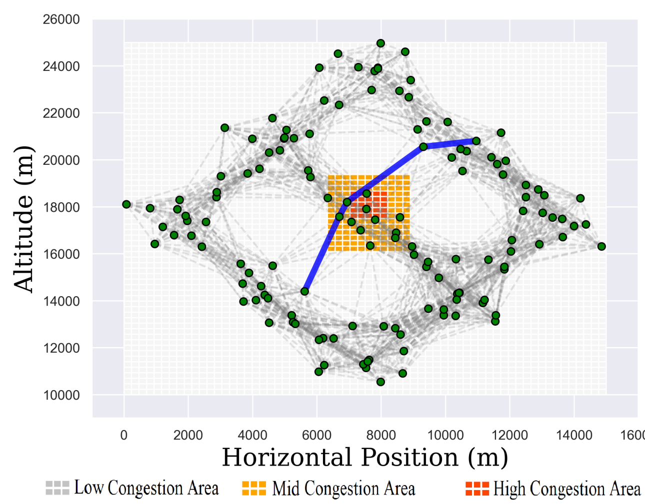



Fig. 22: Path generated from AODV routing scheme.

slowly and the maximum delay is 186 ms without prediction and 119 ms with prediction.

We can see that prediction model boosts up the QoS performance for all cases. Prediction-based routing almost doubles the throughput for AODV protocol. Over 30% increase of throughput can also be observed for bubble routing protocol. Such a prediction is important in THz networks because THz channel is extremely sensitive to link stability, link distance and node altitude. A high mobility could cause unstable links and large packet loss rate. Prediction helps to adjust the antenna beam in the early phase. For example, the system can quickly switch to other relays if a link breakage is going to happen. Therefore, mobility/link state prediction is a significant component in THz routing protocol.

## V. Conclusions

In this research we have built bubble routing protocol for THz links of FANET. It considered the THz channel properties in the air, which are both distance- and altitude-selective. It also used deep learning model to predict the topology evolution trend in each bubble to better prepare the adjustment of the antenna beam and inter-/intra-bubble links. It can avoid high-traffic areas by using the traffic heat map analysis. We have conducted FANET simulations to verify its QoS superiority to conventional routing schemes.

Our next-step work is to further extend bubble routing to general ad hoc THz networks with heterogeneous mobility modes and 3D architecture, and will use deep reinforcement learning to make accurate decisions on how to choose the best bubble chain.

**Table 8.** Simulation Parameters

| Variable Name | Value |
|---|---|
| Node Number | 138 |
| Average Speed | 250 m/s |
| Single Node Mobility Model | Gaussian Markov within 1000 by 1000 meter area |
| Bubble/Cluster Mobility Model | Mission driven |
| Canvas Width Range | 0-16 km |
| Canvas Altitude Range | 10-25 km |
| Data Sending Rate | 100-600 Gbps |
| Max Link Capacity | 1.153 Tbps at altitude=10 km with distance= 1 km and zenith angle = 90 degree |
| Effective Signal Range | 300 meters |
| Transmission Power | 200 mW |
| Reception sensitivity | -95 dBm |
| Queue Size | 64 G |
| Antenna Gain (intra-bubble) | 9 dBi |
| Antenna Gain (inter-bubble) | 10 dBi |

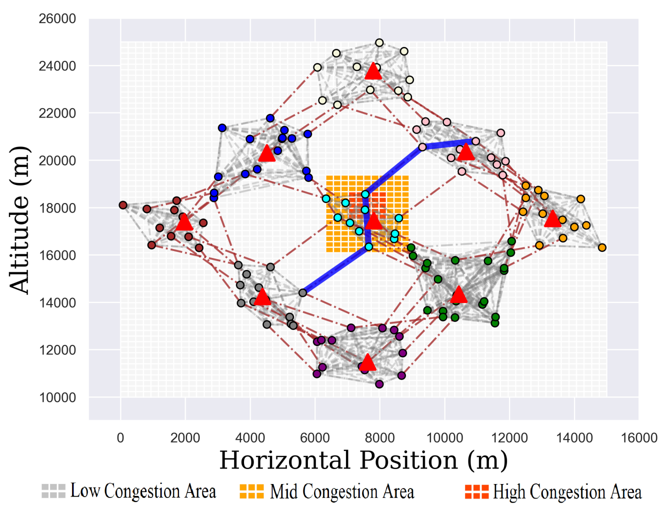



Fig. 23: AODV scheme applied to bubble structure. (The path is highlighted with blue lines)

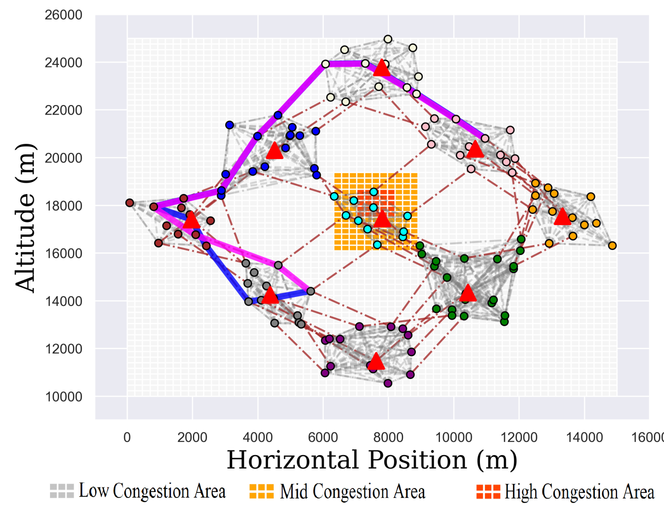



Fig. 24: Traffic path generated from bubble routing.

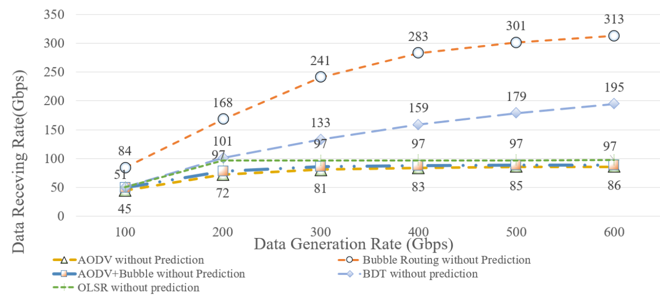



Fig. 25: Throughput (without prediction).

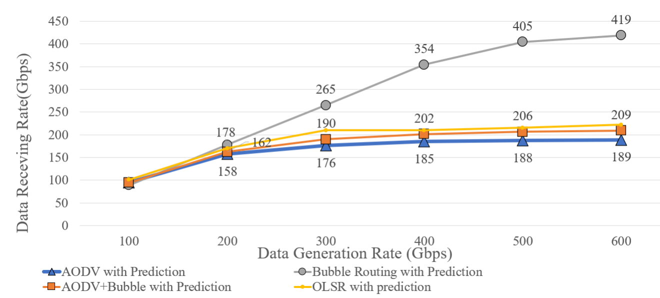



Fig. 26: Throughput (with prediction).

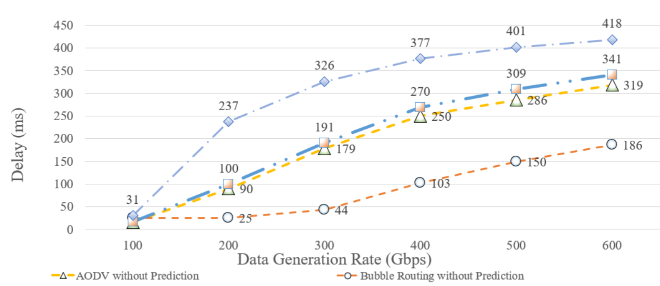



Fig. 27: Delay (without Prediction).

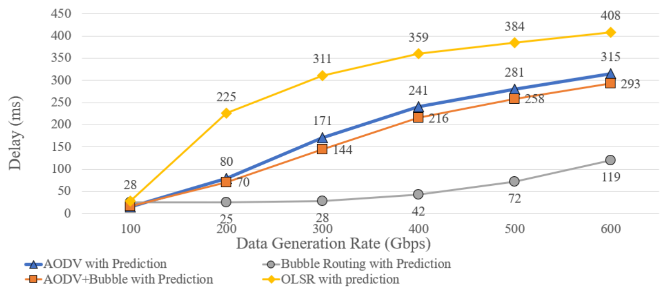



Fig. 28: Delay (with Prediction).

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