Aeronautical Ad Hoc Networks

Ehssan Sakhaee[†], Abbas Jamalipour[†], and Nei Kato[‡]
[†]School of Electrical & Information Engineering, University of Sydney, Australia
[‡]Graduate School of Information Sciences, Tohoku University, Japan

***Abstract*—There has been an enormous growth in Mobile Ad hoc NETworks (MANETs) in land based small to medium size networks with relatively strict power and resources. In this paper the concept of ad hoc networking between aircraft is introduced, which can be considered as a novel approach in increasing the data rate and practicality of future in-flight broadband Internet access. This method also reduces the Internet traffic load on satellite nodes and also propagation delay for real-time traffic transmissions, by effectively bypassing the satellite link for non-real time data. A dynamic routing algorithm is also proposed for efficient routing in this kind of system. A new cost metric for increasing path duration is introduced to assist routing in the proposed ad hoc network.**

I. INTRODUCTION

The wide spread use of on-board broadband Internet access particularly in the case of aeronautical systems is gradually taking off. Already in 2005, Connexion by Boeing [1] has implemented broadband Internet on long-haul flights including Lufthansa, Japan Airlines, Scandinavian Airlines, and many others have signed definite agreements to implement this service on their commercial aircrafts. Although broadband speeds are offered, it is shared among users, and as the deployment of these services continues and more and more users begin exploiting these services, the need for an efficient system model and its management would become an integral part of the system. Furthermore, it is desired to find an alternative approach to bypass the long propagation delay of the satellite link for delay sensitive Internet applications. There have been recent studies in aeronautical satellite communication, where the communication is limited to satellite [2-4]. In [5], the idea of direct communication to ground for Internet access was envisaged.

The proposed extension to the initial model in [5] is to provide direct communications, also among planes. This increases the methods of wireless data communication as shown in Fig. 1. This can be seen as a three-layered topology as shown in Fig. 2, where the top layer is the satellite layer, the middle layer is the aircraft layer, and the bottom layer is the ground station (Earth segment) layer. These layers could effectively interact with each other using inter-layer links.

In this paper the focus will be on the middle layer, where airplanes directly communicate with each other. Due to the high mobility of planes, the network topology of airplane nodes falls into the Mobile Ad hoc NETwork (MANET) category. Hence the ad hoc networking among planes will be the focus of this paper.

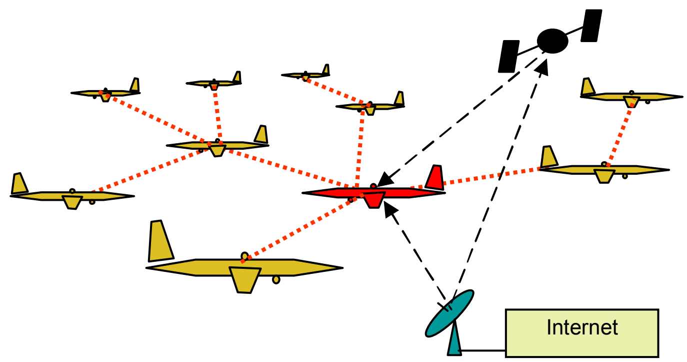

Figure 1. Methods of aeronautical data communications.

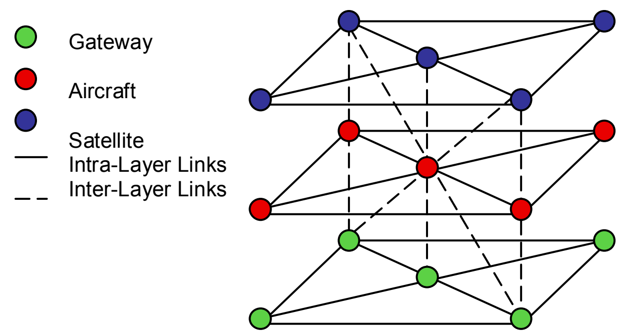

Figure 2. Layered topology of routing in aeronautical systems.

The vast interest in MANETs in the past couple of years has extended the vision of how infrastructure-less mobile nodes can communicate with one another. The primary application of ad-hoc networks has been for small to medium scale devices that are usually restricted by power, bandwidth, and range. Examples of these are the Bluetooth devices and IEEE 802.11 Wireless LAN [6]. However MANETs should not be limited to small devices and localized parameters. It may be possible to extend a MANET to almost a global network level where the mobile entities are large-scale systems having relatively large resources and transmission power. This is especially true when considering cars or commercial aeronautical systems. Additionally, when considering ad hoc networking in the aeronautical system (or any mobile system for that matter), mobility behaviors should be taken into account so that durable links are identified and established between nodes in order for the successful transmission and reception of data. Different mobile devices

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have different mobility properties and characteristics such as speed, direction, randomness, and consistency of motion. The mobility characteristics of mobile entities have a significant effect on the communication and routing of the system. Thus a routing protocol may be more effective when it is not simply generic or a "for all-mobility models and systems" routing protocol. A routing scheme aimed at a particular mobility model or system may scale better for the targeted network.

The main aim of this paper is to propose the concept of ad hoc networking for the aeronautical system, which includes addressing a suitable aeronautical mobility model, propose routing schemes that work effectively with the aeronautical ad hoc network, and demonstration of how the relative stability of nodes is discovered in the routing scheme. It will be shown how selection of stable nodes in this system will improve path and link duration, which is the primary concern in the proposed system.

II. Background and Research Justification

A. The Reality of Aeronautical Ad Hoc Networks

Ad hoc networking among commercial aircraft can be very useful as planes would then be able to share their on-board cached data and Internet access. In fact a whole new ad hoc network between planes can be developed around the globe by having multihop routing among planes. According to the National Air Traffic Controllers Association [7], there are on average 5000 planes in the sky above the United States at any instance. We collected data using the Flight Explorer Personal Edition [8] in April 2005 over a couple of days to verify this. It was observed that the density varies from day to day, and also between different times of the day. There may be from as few as around 600 commercial aircraft to just over 5000 scattered around the United States sky at any given moment, although the density increases towards the east coast for the majority of the time. Fig. 3 shows the aircraft density at 22:15 UTC on 23 April 2005 taken using the Flight Explorer**.** As for Europe, 25,000 aircrafts cross the European sky each day, and it is estimated that this figure would have doubled by 2010 [9]. Indeed, by developing a global network of commercial planes this figure would increase to tens of thousands of planes, forming a gigantic layer of communicating nodes in mid-air.

In the proposed aeronautical mobility model any plane should be able to see at least one other plane at any time in order for multihop routing to become possible. If the Earth's curvature is considered to be the geometrical factor limiting plane-to-plane communication range, then the possible geometrical area of the *communication zone S* shown on Fig. 3 is calculated using $S = \pi\,(2Rh + h^2)$ where R is the radius of the Earth, and h is the altitude of the aircraft. The Earth's radius is approximately 6378 km, and h will be set to 9 km (the average cruise altitude of most commercial and general aviation planes is between 8 km to 11 km).

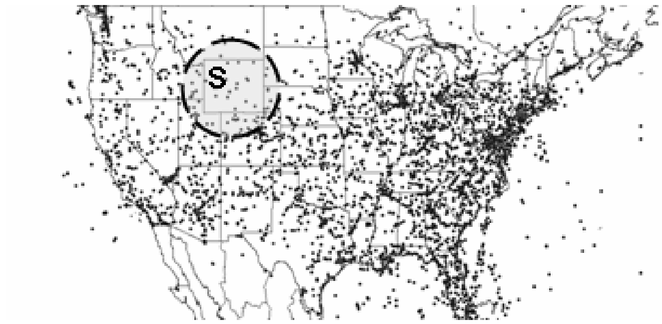

Figure 3. Commercial aircraft density in United States.

From the data collected, since the eastern part of US has a higher airplane density, the lower boundary of 700 planes across the US is chosen as an average number of planes across the region, i.e. an average density of $\lambda \approx 7.6 \times 10^{-5}$ planes/km^2 (for the land area of 9,158,918 km^2). The number of airplanes n in the region S can be worked out using a Poisson distribution, as $p(n,S) = \left((\lambda S)^n / n!\right)e^{-\lambda S}$. The minimum number of planes needed in S is *two* for single-hop and multihop routing to become possible. From Fig. 4 it can be seen that the probability of finding two or even up to a dozen planes within S is close to 100%. Hence with regard to plane density, the scheme of ad hoc networking within US's sky would be feasible. Most commercial passengers on aircraft over a continent may be accessing the same data such as news, information about accommodation, travel and other tourist related information. A survey done in [10] showed that the top services and information that passengers thought most important to use on-board the aircraft were practical information about their destination (transport, hotel, etc), access to general news services, and cultural information about the destination (e.g. history, culture, landmarks etc). In the survey these services also took precedence over sending and receiving emails and real-time multimedia services. These top services have two things in common: They are not real-time services, and they do not occupy enormous amount of disk space on an on-board system; making them ideal for

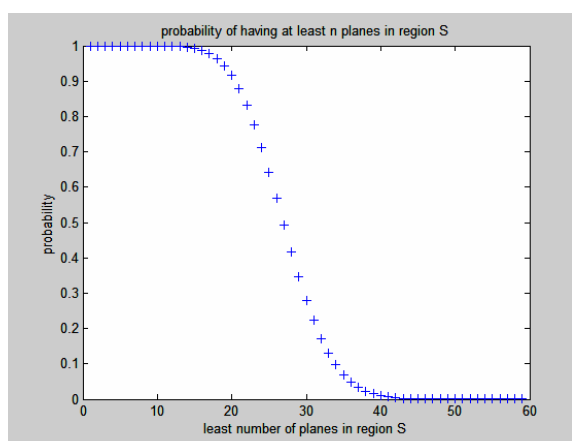

Figure 4. The probability of finding at least n airplanes in region S.

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caching and sharing among hundreds and thousands of passengers every day. Although certain data need to be updated regularly via the Internet, once updated these can be shared across a continent or even the globe via ad hoc networking between planes.

B. MANET Concerns Related to Aeronatical Ad Hoc Networks

Link or path duration in fact is a major concern when it comes to MANETs and it has been a major metric treated in recent works related to these systems [11-13]. The best path in a MANET is not necessarily the shortest path. For example consider a shortest path, which breaks before a download is complete as a result of a node leaving the communication zone.

In recent years there have been many different routing protocols proposed for MANET, some proactive [14-17], on-demand [18-20] and hybrid approaches [21-22], and some location based routing schemes [23-24]. However these routing schemes do not take into account mobility characteristics during route discovery, and consequently path selection does not take into account the mobility of nodes. In [25] the concept of node *stability* is used for routing and proves effective in mobility models where some nodes will eventually come to rest at some stage, however in the aeronautical mobility model nodes are constantly moving (during routing). Node mobility is the primary factor affecting link duration in ad hoc networks. Furthermore, there are certain restrictions imposed by the aeronautical mobility model in the methodology of determining node mobility. For instance the use of power of signals [26] to determine relative node mobility should be avoided as power of signals may be subjected to atmospheric attenuation [27], especially in rainy weather. A more suitable method is to use the Doppler shift of control packets to estimate link duration and relative stability of nodes as outlined in the next section.

III. AD HOC ROUTING AMONG PLANES

A. Aeronautical Mobility and Routing Model

The aeronautical system has certain inherent mobility characteristics that qualify it to have its own unique mobility model. Planes have high speeds, and move in almost linear routes for most of their journeys (until they approach the vicinity of the airport). The aircraft can be identified as a pseudo-linear fast moving mobile entity with no pause time (during routing). Furthermore, it can exhibit group mobility as shown in Fig. 5, when planes commute to and from common regions. The significance of this is explained in the next section. In this mobility model, nodes may also be moving above or below each other, since airplanes are not all at the same altitude, (altitude is based on environmental pressure rather than actual distances above sea level) forming a 3-D layer of mobile nodes (unlike the 2-D ground based ad hoc networks).

Figure 5. Group mobility in aeronautical systems.

B. Aeronautical Routing and Definition of "Best" Path

As mentioned earlier, individual links on a path must be maintained for successful communication. In the proposed aeronautical routing protocol the primary aim is to successfully receive some data *d* from *any* node that can provide the data. Two factors affect link duration: the relative velocity and relative position of nodes on a path with respect to each other. Although the relative position of nodes is a factor, in [28] it was shown that the effect of relative velocity dominates relative position of nodes in the targeted system when it comes to path duration. Furthermore, if a multihop scenario as in Fig. 6 is considered, the best path can be defined as the most stable path, where separate links on the path have long durations. In such a case, nodes on the path have velocities (speed and direction) very close to each other. Referring to Fig. 5 it can be seen that such a scenario is promising in the aeronautical mobility system. The airplanes in Fig. 5 can easily share information over single-hop and multihop routes, without much concern about link expiration (anytime soon).

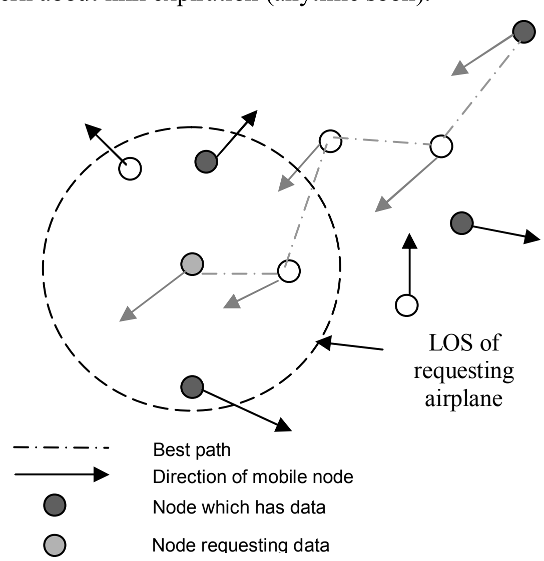

Figure 6. A best path scenario.

However, to more accurately estimate the link duration we must also consider the effect of approaching and receding nodes. Approaching nodes could in general have up to twice the link duration as receding nodes. Thus the *cost* of a link with respect to the estimated link duration can be derived as the *Velocity Link Cost* (VLC) defined as

$VLC = -v$ (if v is negative. i.e. approaching)

$= 2v$ (if v is positive. i.e. receding)

where v is the relative velocity of the two nodes forming the link. The smaller the cost, the better the link with respect to the estimated relative link duration. Finally the best path can be defined as the path with the smallest bottleneck VLC. Note that consistent Quality of Service (QoS) is assumed across the network in this initial model.

C. Doppler Shift of Packets

A property that is a direct consequence of the aircraft's high speed, which affects radio communication, is the Doppler shift that causes apparent change to the frequencies of radio signals transmitted to and from planes. However this apparent drawback can actually assist in selecting more stable paths that have longer link durations. Each (radio transmitted) packet is subjected to Doppler shift [5, 27] which depends on the relative velocity of the replying aircraft to the receiving aircraft. The Doppler shift is the apparent change in frequency of transmitted electromagnetic signals due to the relative motion of the transmitter and receiver [29]. In [5] the concept was used between a mobile node (aircraft) and static nodes (satellites and ground stations). However the nature of the relative Doppler factor changes here, as all nodes are mobile.

For relative velocities v small compared with the speed of light c, the ratio of frequency shift of the expected frequency of received signal f to the observed frequency f_o is given by $f / f_0 = 1 + v/c$. Hence the ratio of frequencies is *proportional* to the relative velocity between the two communicating nodes. It is assumed that all communication uses a constant standard frequency f known by all airplanes. Thus mapping the *Velocity Link Cost* to the *Doppler Value* (link cost) we have

Doppler Value $= -c\,(f / f_0 - 1)$ … (if $f / f_0 < 1$) … *approaching*
Doppler Value $= +2c\,(f / f_0 - 1)$ … (if $f / f_0 < 1$) … *receding*

By observing the Doppler shift of communication between pairs of nodes, the *quality* of the link with regard to link duration (stability) can be determined.

D. Multipath Doppler Routing Algorithm

The proposed on-demand routing protocol *Multipath Doppler Routing (MUDOR),* takes into account mobility as a parameter in its routing procedure. It selects the path with the longest path duration based on the bottleneck *Doppler Value* of the path. It uses the same principle of flooding for route discovery as other on-demand protocols. It also caches the node addresses in the forwarding Route Request (RREQ) packet much like the Dynamic Source Routing (DSR) [18]. MUDOR is designed for pseudo-linear fast moving mobile entities such as the aircraft, which exhibit measurable Doppler shifts to communication signals. It is based on the principle of a node requesting some data d from other nodes that can potentially provide the data. Here there is no single destination, but every node that can provide d becomes a candidate for providing the data to the requesting node. In this routing scheme the aim is also to find a path which is stable enough to ensure complete transfer of the data. An example of this type of routing is accessing cached data from another plane. Furthermore, in order to achieve paths with long link durations, MUDOR considers the different combination of nodes which result in a stable path, which also involves considering non-disjoint paths. This makes the proposed algorithm distinct to other previous reactive algorithms used in MANETs, as previous algorithms only consider disjoint paths by dropping identical request packets. The extra flooding of identical packets is reduced by a mechanism where only packets with smaller Doppler Values than the previous identical packet are forwarded, and the rest are discarded, hence significantly reducing flooding. Also, a maximum hopcount field is incorporated onto the RREQ packet which is decremented at each node, to avoid extended request flooding throughout the network.

There are several Doppler values used in MUDOR.

1. The Doppler (shift) Value experienced by the packet as it travels from the previous node to the current node. This is termed as Packet's Doppler Value (PDV).
2. The Packet Header Doppler Value (PHDV) is the bottleneck Doppler Value in the packet header. The PHDV is updated at each node (both on the RREQ and RREP) by being replaced by the larger of the two values of PDV and PHDV.
3. The minimum Doppler Value for the same identical packet request stored at a receiving node, termed Best Doppler Value So Far (BDVSF). This is used as a discriminator for identical request packets.

Hence only identical packets which provide a smaller Doppler Value are forwarded. Also each node adds its own address to the RREQ packet cache addresses, before forwarding the packet. Assume that a user on aircraft *A* wishes to listen to a rare song that does not exist on the on-board database of *A*. The song would have an identifier "id". The basic algorithm is as follows (1 request coming from the requesting node *A*).

Request Node *A*: Broadcasts RREQ with request for "id" to all (LOS) single-hop nodes.

Receiving Node (RREQ rebroadcasting): If PDV > PHDV, replace PHDV with PDV. If PHDV < BDVSF, BDVSF = PHDV, if the node can provide data, produce a reply (RREP), else rebroadcast (and decrement hopcount). If PHDV > BDVSF, drop the packet.

Receiving Node (RREP forwarding): Update PHDV at each node. If receiving node is requesting node, store RREP in routing table, else forward the packet to next node. Requesting node (A) stores all known paths in the routing table from smallest to largest Doppler Values (PHDV). It chooses the smallest cost path to retrieve requested data. If the first path fails, choose the second path and so on. This is the multipath mechanism adopted in MUDOR.

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IV. SIMULATION OF ROUTING PROTOCOL

Two sets of simulations are performed, one demonstrating the effect of node density using single hop and the other looks at a multihop scenario with regards to range. The simulations were developed using the Java programming language.

A. Simulation for Single-hop in Relation to Node Density

In order to demonstrate the effect of relative velocity on link duration, random scenarios are created with varying node densities. Each node moves in a single direction at a constant speed for a fixed period of time. There is one requesting node, and all other nodes are candidate data providers.

In the simulation scenarios when an associated node leaves the requesting node's LOS, a new routing decision takes place. There are two routing schemes. Scheme 1 works on the simple principle as follows:

1. *Choose closest node for routing.*
2. *Repeat when associated node leaves LOS.*

Scheme 2 is performed as follows:

1. *Out of nodes within range, select the node with closest relative velocity.*
2. *Repeat when associated node leaves LOS.*

Scheme 2 takes relative velocity into account when choosing nodes for data retrieval, whereas Scheme 1 is simply the traditional "shortest path" routing scheme and chooses the closest node (distance is used as the metric). The two routing schemes are simulated and the average link duration for the entire simulation period for each routing scheme is calculated.

Two sets of simulations were carried, one showing the average link durations with respect to number of handoffs by keeping the number of nodes to a constant 100 over a period of time. Table I shows the results. The second simulation involved increasing node density and observing the effect on the two routing schemes in relation to the number of handoffs during the total simulation period. The nodes are simulated in an area of $111m^2$. Results are shown in Fig. 7.

TABLE I. SIMULATION RESULTS FOR SNGLE-HOP

Scheme	*Average Link Duration (s)*	*No. of Handoffs*
1	6.74	750
2	26.49	200

Note that the number of handoffs is inversely proportional to the link duration, as the average link duration equals total simulation time divided by the number of handoffs. We note that as the number of nodes (i.e. node density) increases, there are more nodes within range for routing. In Scheme 1, simply the closest one is chosen, whilst in Scheme 2, the nodes that have the closest relative velocity to the requesting node are chosen. As the node density increases, there are more candidate nodes, and hence in Scheme 2, there are more nodes

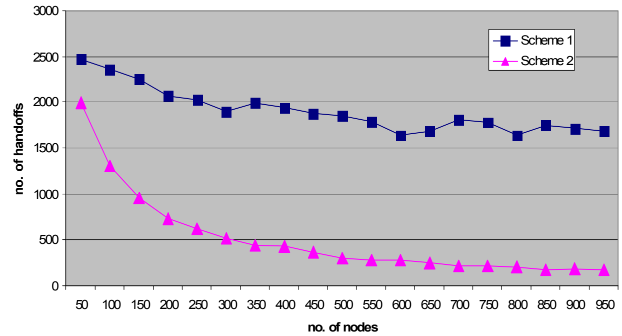

Figure 7. Number of handoffs versus node density.

that have closer velocities to the requesting node, and since those nodes are chosen, the number of handoffs decreases, and hence link duration increases. From the results, it is clear that Scheme 2 that integrates the relative velocity as the mobility parameter into path selection outperforms Scheme 1, especially when node density increases.

B. Simulation for Multihop With Regard to Communication Range for a Real World Scenario

In this simulation an actual real world scenario is simulated with node speeds of 840 km/h and average intra-continental flights lasting for 230 minutes. The percentage of nodes that contain the requested data is set to 1%; maximum number of hops is set to 6. An average plane density of 5000 nodes is used across an area of 9 million km^2 [7]. The nodes are randomly generated across this land area. The range of communication is varied between 200 km and 600 km. This limited range is used in order to limit the effect of signal attenuation and path loss and ensure better communication quality between aircrafts. Two routing schemes are simulated. The DSR shortest path routing algorithm and the other is the MUDOR algorithm. The shortest path metric used is distance. Table II and Fig. 8 show the results of this simulation.

TABLE II. MULTIHOP SIMULATION FOR VARIABLE RANGE

Algorithm	*No of handoffs*	*No. of hops*	*Ave. path distance*	*Range (Km)*
DSR	13	3	600.9968	200
MUDOR	9	4	960.6499	200
DSR	8	2	221.654	400
MUDOR	3	3	1123.872	400
DSR	6	2	292.8169	600
MUDOR	3	3	616.957	600

In these sets of simulations we can see that MUDOR outperforms DSR (and hence other shortest path algorithms) in terms of number of handoffs during the whole simulation time, which reflects the longer path duration as a result, although this is at the price of increased average path distance and number of hops. Note that as the range of communication is increased, the number of handoffs decreases during the simulated aircraft journey.

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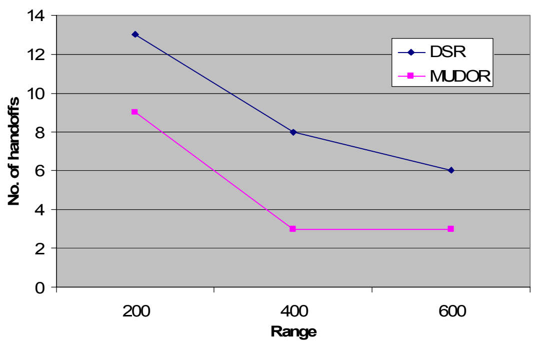

Figure 8. Number of handoffs vs. Range.

V. Conclusions and Future Works

In this paper the concept of aeronautical ad hoc networks is introduced and an on-demand routing scheme suitable for this kind of system is proposed. A novel approach of using Doppler shift of packets to identify relative stability of nodes in the routing scheme is demonstrated. In future works clustering of planes should be considered to enhance scalability of this large-scale system. Future research will also focus on integrating QoS into the cost metric. The integration of the ad hoc layer of the aeronautical system (middle layer of Fig. 2) with the rest of the aeronautical routing model should also be a part of future research.

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